
NASA'S MICROGRAVITY RESEARCH PROGRAM

1997

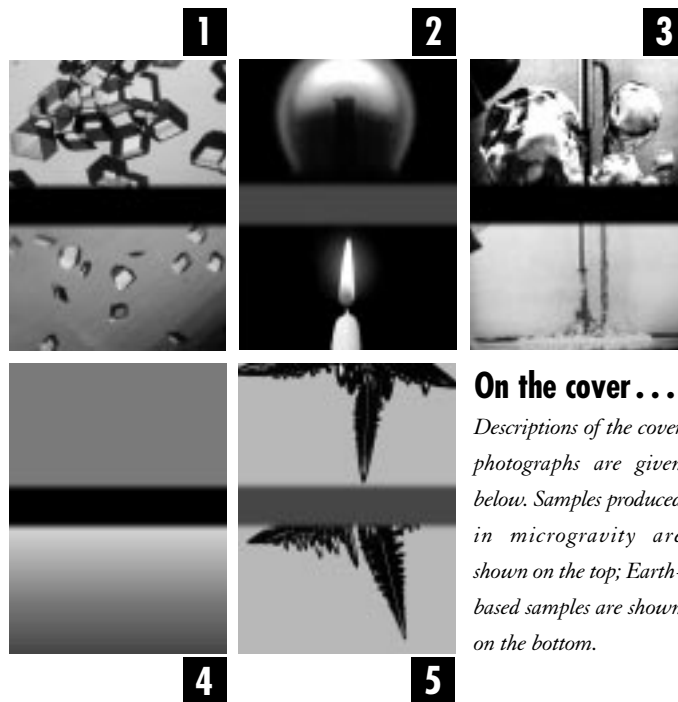
A N N U A L
R E P O R T

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National Aeronautics and
Space Administration

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On the cover . . .

Descriptions of the cover photographs are given below. Samples produced in microgravity are shown on the top; Earth-based samples are shown on the bottom.

1 Biotechnology

Crystals of recombinant human insulin grown in microgravity are much larger than crystals of the protein grown on Earth. Insulin is a protein that enables our bodies to turn sugar, starches, and other food into energy. Understanding insulin's molecular structure may lead to better treatments or even a cure for diabetes.

2 Combustion Science

In microgravity, candle flames appear very different than they do on Earth — the reduction in buoyancy-induced convective flows results in a spherical, soot-free, blue flame. In contrast, convective flows created by Earth's gravity cause a flame to be teardrop-shaped and carry soot to the flame's tip, turning it yellow.

3 Fluid Physics

In microgravity, when a liquid is heated from the bottom until it reaches its boiling point, bubbles of heated gas stay attached to the container near the source of heat longer and grow larger than they would on Earth, where small bubbles of heated gas form near the bottom of the container and are carried to the top by buoyancy-induced convection.

4 Fundamental Physics

A sample of liquid helium in microgravity experiences a uniform distribution of pressure throughout. However, in Earth's gravity, the same sample experiences a nonuniform pressure distribution, with the pressure at the bottom of the sample greater than that at the top. Microgravity conditions enable scientists to more effectively probe the underlying physics of the phase change from liquid helium to superfluid helium, which is directly dependent on temperature and pressure. The uniform pressure in the microgravity sample allows the entire sample to undergo the phase change at once.

5 Materials Science

Dendrites are microscopic crystalline structures that form as some molten materials, including metals, solidify. Here, dendrites of pivalic acid form from melted material. Under microgravity conditions, the tip of the dendrite is larger and more blunt, and the sample grows more slowly than the Earth-based sample. While the side branches of the sample grown in microgravity grow only slightly, those in the Earth-based sample experience augmentation as gravity helps transport heat out of the way of the growing branches.

The ongoing challenge faced by NASA's Microgravity Research Program is to work with the scientific and engineering communities to secure the maximum return from our nation's investments by (1) assuring that the best possible science emerges from the science community for microgravity investigations; (2) ensuring the maximum scientific return from each investigation in the most timely and cost-effective manner; and (3) enhancing the distribution of experiment data and application of results to maximize their benefits.

NASA Continued to Build a Solid Community of Microgravity Researchers for the Forthcoming International Space Station Era

During fiscal year (FY) 1997, the Microgravity Research Program selected investigations from the 1996 biotechnology, fluid physics, fundamental physics, and materials science NASA Research Announcements (NRAs). The NRA in combustion science will be released in early FY 1998. Principal investigators (PIs) chosen from these NRAs will form the core of the program at the beginning of the International Space Station (ISS) era.

The approximately \$105 million research budget supported the work of 329 PIs whose research was published in 576 journal articles and addressed in 647 technical presentations. The release of the National Research Council's review of microgravity research in support of NASA's Human Exploration and Development of Space (HEDS) enterprise confirmed that microgravity research has an important role to play in the success of future exploration missions. In preparation for supporting HEDS, the Microgravity Research Division began to focus its research efforts on HEDS goals.

Continuing Strides Were Made in Interagency, International, and Intergovernmental Cooperation

Cooperation with the National Institutes of Health (NIH) continued to address the technical challenges of three-dimensional tissue growth, crystallization of high-quality protein crystals, and early detection of cataracts through the support of multidisciplinary research teams. These teams allow some of the best American scientists and bioengineers to address complex problems and accelerate technology development and transfer. Through NASA-NIH cooperation, NASA has funded 28 research proposals and has also supported NIH-approved researchers to test tissue samples in NASA bioreactors at Johnson Space Center.

Data from microgravity research equipment on the Russian space station, *Mir*, continue to be analyzed by NASA microgravity scientists and engineers in preparation for operation of the ISS. Planning for ISS facilities continued with respect to the Biotechnology Facility, the Fluids and Combustion Facility, the Low-Temperature Microgravity Physics Facility, and the newly

planned Materials Science Research Facility and Microgravity Science Glovebox facility.

Letters of agreement with Japan, Canada, and Germany have improved the research facilities available to U.S. microgravity researchers. Japan's Large Isothermal Furnace (LIF), Canada's Microgravity Isolation Mount (MIM), and Germany's electromagnetic containerless processing facility (TEMPUS) are important resources for investigations in the Microgravity Research Program.

The First Microgravity Science Laboratory Mission and Other Space Shuttle Missions Yielded Significant Results for Microgravity Investigations

The first Microgravity Science Laboratory (MSL-1) mission and its reflight (MSL-1R), as well as several Space Transportation System (STS) missions to *Mir*, yielded a wealth of microgravity data in FY 1997. MSL-1 and MSL-1R included the Middeck Glovebox facility, designed to support experiments that require isolation from the shuttle or space station environment while allowing crewmembers to conduct small-scale investigations and manipulate hardware and materials. Also on the MSL missions, four important pieces of hardware supported biotechnology experiments in protein crystallization and tissue culture: the Protein Crystallization Apparatus for Microgravity, the Single-Locker Thermal Enclosure System, the Second-Generation Vapor Diffusion Apparatus, and Hand-Held Diffusion Test Cells. FY 1997 STS missions carried multiple experiments that were conducted in three internationally developed facilities — LIF, MIM, and TEMPUS — thus broadening the opportunities for international cooperation in space research.

The Microgravity Research Program Expanded Education and Outreach Activities

Microgravity News, which provides quarterly updates on NASA's Microgravity Research Program, reached increasing numbers of people in the past year. The total distribution of each issue of the newsletter reached over 9,000 for calendar year 1997. Progress continued in FY 1997 on the Microgravity Research Program World Wide Web sites, part of an ongoing effort to integrate numerous microgravity web pages.

Through NASA's Graduate Student Research Program, seven graduate students received funding to perform ground-based microgravity research in FY 1997, supporting a commitment to encourage the next generation of microgravity researchers. More than 10,000 each of microgravity science educational posters, teacher's guides, and supplementary curricular materials were distributed at various conferences. Also, over 1,400 teachers requested that they be added to the microgravity education and outreach mailing list. This brought the total number of educators on the mailing list to 3,321 (including 726 kindergarten and elementary, 826 middle school, 1,473 high school, and 296 other educators).

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This fiscal year (FY) 1997 annual report describes key elements of the NASA Microgravity Research Program (MRP) as conducted by the Microgravity Research Division (MRD) within NASA's Office of Life and Microgravity Sciences and Applications. The program's goals, approach taken to achieve those goals, and available resources are summarized. A "snapshot" of the program's status at the end of FY 1997 and a review of highlights and progress in ground- and flight-based research are provided. Also described are major space missions that flew during FY 1997, plans for utilization of the research potential of the International Space Station, the Advanced Technology Development (ATD) Program, and various educational/outreach activities. The MRP supports

investigators from academia, industry, and government research communities needing a space environment to study phenomena directly or indirectly affected by gravity.

Natural extensions of traditional Earth-based laboratory science, the experiments conducted under the MRP benefit from the stable, long-duration microgravity environment available on orbiting spacecraft. The microgravity environment affords substantially reduced buoyancy forces, hydrostatic pressures, and sedimentation rates, allowing gravity-related phenomena to be isolated and controlled, and permitting measurements to be made with an accuracy that cannot be obtained in ground-based laboratories.

Table 1 **FY 1993–1997 research task summary: overview information and statistics**
(includes some continuing projects at no additional cost)

	FY 1993	FY 1994	FY 1995	FY 1996	FY 1997
Number of principal investigators	196	243	290	358	329
Number of co-investigators	268	252	287	396	375
Number of research tasks	243	316	347	508	414
Total number of bibliographic listings	767	944	1,200	1,573	1,428
■ Proceeding papers	110	145	140	237	177
■ Journal articles	446	371	526	600	576
■ NASA technical briefs	6	13	11	14	10
■ Science/technical presentations	201	391	509	706	647
■ Books/chapters	5	24	14	16	18
Number of patents applied for or awarded	7	1	1	2	4
Number of students funded	329	434	534	780	748
Number of degrees granted based on MRD-funded research	61	125	178	247	243
Number of states with funded research (including District of Columbia)	32	36	34	35	36
FY MRD Budget (\$ in millions)	179.3	188	163.5	159	105.3

The Microgravity Research Program supports both basic and applied research in five key areas:

- **Biotechnology** — focusing on macromolecular crystal growth as well as the use of the unique space environment to assemble and grow mammalian tissue.
- **Combustion science** — focusing on the processes of ignition, flame propagation, and extinction during combustion of gaseous, liquid, and solid fuels, and on combustion synthesis in a low-gravity environment.
- **Fluid physics** — including aspects of fluid dynamics and transport phenomena affected by the presence of gravity.
- **Fundamental physics** — including the study of critical phenomena; low-temperature, atomic, and gravitational physics; and other areas of fundamental physics where significant advantages exist for studies in a low-gravity environment.
- **Materials science** — including electronic and photonic materials, glasses and ceramics, polymers, and metals and alloys.

Experiments in these areas are typically directed at providing a better understanding of gravity-dependent physical phenomena and exploring phenomena obscured by the effects of gravity. Scientific results are used to challenge or validate contemporary scientific theories, identify and describe new experimental techniques that are unique to the low-gravity environment, and engender the development of new theories explaining unexpected results. These results and the improved understanding accompanying them can lead to improved combustion efficiency and fire safety; reduced combustion-generated pollutants; the development of new technologies in industries as varied as medicine,

chemical processing, and materials processing; the development or improvement of pharmaceuticals; and the expansion of fundamental knowledge in a broad range of science disciplines destined to become the foundation for scientific and technological discoveries in the future.

A complementary document to this MRP annual report is the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998. Detailed information on the research tasks funded by the MRD during FY 1997 is listed in that report, which serves as an excellent reference for supplementary information to this annual report. Also of interest is the *NASA Microgravity Science and Applications Program Strategic Plan*, issued in June 1993, a guide for development and implementation of the MRP plans and activities to the year 2000. The *Marshall Space Flight Center (MSFC) Strategic Implementation Plan*, January 1996, describes MSFC's Lead Center role for the MRP. Another complementary document is NASA's *Microgravity Technology Report*, first published in December 1995, summarizing advanced technology development and technology transfer activities through FY 1994. The most recent edition of this report was published in 1998.

Table 1 summarizes information from the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997* that may be of particular interest to the reader. Data for FY 1993–1996 are shown for comparison with FY 1997 statistics.

Table 2 lists the number of research tasks and types performed at each NASA center for FY 1993–1997.

Table 2 Microgravity research tasks and types by fiscal year
(responsibilities by center)

Center	Ground					Flight					ATD					Center Totals				
	1993	1994	1995	1996	1997	1993	1994	1995	1996	1997	1993	1994	1995	1996	1997	1993	1994	1995	1996	1997
Jet Propulsion Laboratory	29	27	28	45	23	7	7	5	7	5	3	3	3	3	39	37	36	55	31	
Johnson Space Center	11	10	34	32	42	1	0	1	1	1	0	0	0	1	12	10	35	34	44	
Langley Research Center	5	3	3	2	0	2	2	2	1	1	1	0	0	0	8	5	5	3	1	
Lewis Research Center	87	131	125	203	137	29	35	32	46	40	5	5	6	6	7	121	171	163	255	184
Marshall Space Flight Center	36	62	76	124	117	25	25	25	32	31	2	4	6	4	5	63	91	107	160	153
Goddard Space Flight Center	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	
Research Task Totals	168	233	266	406	319	64	69	65	87	78	11	13	16	15	17	243	315	347	508	414

To use the microgravity environment of space as a tool to advance knowledge; to use space as a laboratory to explore the nature of physical phenomena contributing to progress in science and technology on Earth; and to study the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth's boundaries.

—From the Microgravity Research Program's Mission Statement

During fiscal year (FY) 1997, the Microgravity Research Program's lead center for microgravity research was established. The plan to implement the lead center at Marshall Space Flight Center was signed by Arnauld Nicogossian, associate administrator for the Office of Life and Microgravity Sciences and Applications at NASA headquarters (HQ), and by Wilbur Trafton, NASA HQ associate administrator for the Office of Space Flight. The goals listed below were established for the Microgravity Research Program for FY 1997.

Goal 1

Sustain a leading-edge research program focused in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science that effectively engages the national research community.

Goal 2

Foster an interdisciplinary community to promote synergy, creativity, and value in carrying out the research program.

Goal 3

Enable research through the development of an appropriate infrastructure of ground-based facilities, diagnostic capabilities, and flight facilities/opportunities, and promote the use of smaller apparatus.

Goal 4

Promote the exchange of scientific knowledge and technological advances among academic, governmental, and industrial communities. Disseminate results to the general public and to educational institutions.

Goal 5

Raise the awareness of the microgravity research community regarding the long-term direction of the Human Exploration and Development of Space enterprise, and discuss with the community the role of microgravity research in support of agency objectives.

3 Program Approach for FY 1997

Program Overview

The Microgravity Research Program (MRP) enables NASA to meet its mission of advancing and communicating scientific knowledge; using space for human enterprise; and researching, developing, verifying, and transferring advanced space and related technologies by using the low-gravity or “microgravity” environment of space for research. Specifically, the MRP performs the following actions:

- Uses the microgravity environment of space as a tool to advance knowledge.
- Uses space as a laboratory to explore the nature of physical phenomena, contributing to progress in science and technology on Earth.
- Studies the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth’s boundaries.

During fiscal year (FY) 1997, the MRP sustained a leading-edge research program, focused on the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science, that effectively engaged the national research community. A unique characteristic of the program is the utilization of the NASA Research Announcement (NRA) to solicit research proposals in the five science disciplines listed above. As in previous years, all investigations selected for funding in FY 1997 were reviewed by external peer review panels comprised of leading experts in each of the five fields of study. This use of peer review assures that the research that is proposed and selected is of the highest caliber and merit and beneficial to the advancement of the United States. Selections within each of the five science disciplines range from relatively low-resource ground-based research, required to advance analytical and experimental studies, to substantial space-based experiments, which require the relative absence of gravity to observe unique phenomena and behaviors typically masked by the effects of Earth’s gravity.

During FY 1997, NASA continued to work toward the completion of investigations selected for funding in previous years. Additionally, new selections were made in biotechnology, fluid physics, fundamental physics, and materials science. In total, NASA received 657 proposals in response to the NRAs that were released in 1996. Of those proposals, 145 researchers were selected in 1997 to receive grants worth a total of approximately \$58 million for conducting ground- and space-based research. The breakdown of recipients by discipline is as follows: biotechnology, 36; fluid physics, 39; fundamental physics, 26; and materials science, 44. Selection of grant recipients in combustion science will take place in FY 1998.

As in the past, the Microgravity Research Program continued to utilize expert advisory groups to guide and validate the value and merit of research conducted in microgravity. The microgravity discipline working groups, which are responsible for maintaining an overview of the efforts in the discipline areas of biotechnology, combustion science, fluid physics, and materials science, continued the process of identifying the most promising areas for scientific investigation and the most advantageous approaches for experimentation, recommending discipline refinements and science priorities and providing an annual program assessment. Of particular note was the charter of a working group for the relatively new field of fundamental physics; the group held its first meeting in FY 1997. Program content, plans, and priorities were reviewed periodically by the Microgravity Research Advisory Subcommittee and the Space Station Utilization Advisory Subcommittee. These subcommittees report to the Life and Microgravity Sciences and Applications Advisory Committee, which reports to the NASA Advisory Council. Additionally, a special committee was convened at the request of NASA to assure that the focus of materials science research aboard the International Space Station (ISS) was of the highest caliber and merit. This group, formed under the auspices of the National Research Council’s Space Studies Board, reviewed and confirmed the nation’s need to advance materials science research.

In FY 1997, the Microgravity Research Program continued to support its research community through ground- and space-qualified apparatus, facilities, and carriers. In support of the relatively large number of analytical and experimental studies requiring a short-duration microgravity environment, ground facilities such as drop tubes and drop towers, and carriers such as parabolic aircraft and suborbital rockets were made available. These facilities and carriers afford from 2.2 seconds to 12 minutes of microgravity, allowing researchers relatively low-cost access to a microgravity environment. To support the space-based investigations, the program selected the most cost-effective option from a broad range of instrumentation, apparatus, and carriers. Primary carriers utilized to advance research requiring a longer-duration microgravity environment included the Space Transportation System (STS) space shuttle missions and the Russian space station, *Mir*. Additionally, work continued toward the development of facilities to be housed aboard the ISS, which will allow researchers continuous access to a microgravity environment. Launch of ISS component modules is scheduled to begin in 1998.

Space Transportation System Program

FY 1997 saw the flight of five space shuttle missions with significant microgravity experiments aboard: the STS-81 mission in January; the first Microgravity Science Laboratory (MSL-1)/STS-83 in April; the reflight of MSL (MSL-1R)/STS-94 in July; STS-85 in August; and STS-86 in September. In total, the space shuttle operated for 376 hours in FY 1997, and a number of microgravity investigations took place during its missions. STS-81 supported one materials science investigation. MSL-1 and MSL-1R supported 3 biotechnology investigations, 4 combustion science investigations, 5 investigations in fluid physics, and 16 materials science investigations. STS-85 supported one investigation each in biotechnology, combustion science, and fundamental physics. The STS-86 mission supported three investigations in biotechnology, one investigation in fluid physics, and one materials science investigation. In late 1997, the fourth United States Microgravity Payload (USMP-4) mission flew in support of a number of microgravity investigations. Details and a summary of experiment results will be available in the FY 1998 annual report.

At the request of the Microgravity Research Program Office, representatives from Marshall Space Flight Center's Program Development (PD) organization have been investigating alternatives to using the space shuttle for performing research in a low-gravity environment. With this goal in mind, PD is actively pursuing non-shuttle carriers/launch systems such as balloons; sounding rockets; X-34s; and commercially available, expendable launch vehicles for microgravity payload utilization. It is anticipated that the results of this study will provide the necessary information required to begin planning in FY 1999 for potential microgravity research use of these carriers.

Space Station *Mir*

During FY 1997, the MRP continued to participate in the NASA/*Mir* Phase 1 program, with the goals of mitigating risk in scientific, technological, logistical, and operational planning for use of the ISS; characterizing the microgravity environment on *Mir*; and conducting specific U.S. investigations in microgravity research disciplines. The MRP continued to utilize modified space shuttle experiment apparatus, flight samples, science operations, and data analysis/procedures in order to allow U.S. investigators to fully maximize the capabilities of Space Station *Mir*.

Mir research and support provided early science opportunities during Phase 1 through long-duration science investigations conducted aboard *Mir*, as well as shorter-duration science investigations on the space shuttle rendezvous missions to *Mir*.

In FY 1997, the MRP significantly increased its participation in scientific experiments conducted on *Mir*. During this period, three investigative facilities were located on board: the Biotechnology System (BTS), the Microgravity Glovebox (MGBX), and the Microgravity Isolation Mount (MIM). Thirteen long-duration investigations were performed in these facilities. An international cooperative effort was used to transport payloads to these facilities on *Mir*, using both U.S. STS flights and Russian launch vehicles.

During FY 1997, new technology for protein crystal growth and bioreactors for cell and tissue growth were tested. Samples were exchanged during shuttle flights to *Mir*. These technologies appear to be promising, based on FY 1997 work. The BTS supported biomedical research during the STS-86 flight of the Biochemistry of Three-Dimensional Tissue Engineering (BIO-3D) experiment. BIO-3D will help scientists design successful tissue culture experiments for the ISS and may also contribute to our fundamental understanding of life systems while in long-term low-gravity conditions.

One of the first pieces of hardware launched to *Mir* was the MGBX. This facility provides work space, filtration, video recording, lighting, and containment control capabilities to support a large array of on-orbit investigations. During the past year, the MGBX provided investigative resources to support one biotechnology protein crystal growth experiment, one combustion experiment, and three fluid physics experiments. In FY 1997, the MGBX on *Mir* operated for over 1,000 hours.

To extend the MRP's international cooperation efforts, the Canadian-sponsored MIM facility was included on *Mir*. This valuable piece of hardware was launched on an early flight to *Mir* and has provided acceleration isolation for three experiments: the Canadian Protein Crystallization Experiment, the Queen's University Experiment in Liquid Diffusion, and the Liquid Metal Diffusion experiment.

The MRP continues to collect data and gain experience in conducting long-duration space flight operations and investigations during Phase 1. The knowledge and technique refinement acquired through various projects will optimize science planning, development of hardware systems and supporting operations, and science return for the ISS. Many lessons have been learned from Phase 1 payload developers and science teams. These lessons are being analyzed in order to improve our future ISS processes and our ability to support a continuous orbiting laboratory.

International Space Station

The development of the ISS is laid out in three phases. Phase 1, which is currently under way, includes up to nine shuttle-*Mir* docking missions. Phase 2 will begin with the launch of the U.S.-funded/Russian-built and -launched Functional Cargo Block, and will include limited science capabilities. Phase 3 follows and will involve the completion of the pressurized volume space and crew accommodations by integrating the international modules and the U.S. Habitation Module.

During FY 1997, the MRP continued development of its dedicated research facilities for use aboard the ISS. The Biotechnology Facility (BTF), targeted for protein crystallization, tissue culture, and tissue engineering, neared completion of its definition phase. The BTF is scheduled for launch and integration in 2003. The Fluids and Combustion Facility (FCF), designed for a variety of experiments, including investigations in flame spread, turbulent flow, and condensed fuel combustion, completed its requirements definition phase. Launch of the FCF's components is scheduled to begin in 2001. The test infrastructure for the Low-Temperature Microgravity Physics Facility (LTMPF) was completed in FY 1997. The LTMPF, designed for investigations in fundamental physics, is scheduled to launch in 2004. The Materials Science Research Facility (MSRF), which was designed to expand the range of materials science investigations possible on the ISS, entered its accommodations definition phase. Launch of the MSRF's components is scheduled to begin in 2001. The Microgravity Science Glovebox (MSG) completed its preliminary design review in April and will begin its critical design review in early FY 1998. The MSG, which was designed to support investigations in all of the microgravity science disciplines, as well as some commercial payloads, is scheduled to launch in 2000.

Exploration

The Microgravity Research Program Office (MRPO) began an effort in late FY 1997 to focus a portion of its research on supporting the development of new technologies required for human exploration of the Moon and Mars. This effort was initiated with a microgravity exploration workshop, which included members of the Mars Exploration Working Group, managed by Johnson Space Center; the Jet Propulsion Laboratory; and members of the NASA academic and industrial microgravity research communities. Areas of potential microgravity research were identified based upon Moon/Mars mission requirements and technology needs. These research areas have been translated into performance goals that will define scientific and resource requirements for implementation in future NRAs. Six grants were awarded for investigations selected

from the FY 1996 materials science NRA that will provide data and scientific information to support the Moon/Mars exploration effort. In addition, an experiment designed to characterize dust and soil on Mars during the Mars Surveyor Program 2001 mission has been initiated.

Cooperative Efforts

National Institutes of Health

The FY 1997 NASA appropriations included augmentations for collaborative NASA-National Institutes of Health (NIH) biotechnology programs. In using these funds, NASA emphasized the following areas:

- Continuation of joint NASA-NIH centers to accelerate the transfer of NASA technology and allow its application to biomedical research.
- Development of advanced tissue culturing technology and application of this breakthrough technology to biomedical research and developmental biology.
- Development of advanced protein crystal diagnostic technologies to advance structural biology and drug design to fight a number of diseases.

The NASA-NIH collaboration offers an opportunity to address the technical challenges of three-dimensional tissue growth, crystallization of high-quality protein crystals, and the early detection of cataracts by supporting multidisciplinary research teams. These research teams allow the best American scientists and bioengineers to address these complex problems and accelerate development of the technologies. For acceleration of the pace of technology transfer in the biotechnology areas begun under the NASA-NIH interagency agreement, two multidisciplinary research centers are currently supported: the Massachusetts Institute of Technology in Cambridge, Massachusetts, and the Wistar Institute in Philadelphia, Pennsylvania. Through NASA-NIH cooperation, NASA has funded approximately 28 research proposals and has also supported NIH-approved researchers in testing tissue samples in NASA bioreactors at Johnson Space Center. This has proven to be a very important undertaking in getting researchers to test NASA technology and in gaining acceptance in the larger biomedical community.

During FY 1997, collaborations between NASA and NIH researchers resulted in the first-ever laser light scattering investigation of layers of the eye's lens. Scientist's observed that protein cells in the samples varied as a function of the age of the eye, and they were able to look at a precise image of protein cells on each layer of the lens. In September, the Internal Review Board of the NIH's National Eye Institute approved the protocol for studies of cataracts in human patients using the laser light scattering technique.

The MRP also continued collaborative work with the NIH Laboratory for Structural Biology to develop the next generation of X-ray diagnostic tools for laboratory use. Using new technology, early development has shown this X-ray system to produce a much brighter beam with a significant reduction in power use. This cooperative arrangement will include developing standard manufacturing processes and infusing this new technology into laboratories across the country.

National Institute of Child Health and Human Development

A cooperative effort continued with the National Institute of Child Health and Human Development to transfer NASA's bioreactor technology for use in AIDS research. Researchers are using cultures of human tonsil, lung, adenoid, and lymph node tissues to assess infectivity of the HIV virus on such tissues.

Juvenile Diabetes Foundation

In FY 1997, NASA entered into a cooperative arrangement with the Juvenile Diabetes Foundation to establish the clinical feasibility of islet cell transplantation, including the ability to grow and preserve pancreatic islet cells and to transplant them with various means of protection, including encapsulation. If successful, restoration of normal blood sugar levels would mark a significant advance in the treatment of diabetes. Even though efficient replacement of insulin would not necessarily "cure" Type 1 diabetes, because the autoimmune process would continue unabated, progress in this area is considered a major step.

International Cooperation

Two furnaces for materials science investigations, the German-designed Electromagnetic Containerless Processing Facility (TEMPUS) and Japan's Large Isothermal Furnace (LIF), flew aboard MSL-1. TEMPUS allows metals to be cooled to below their freezing points without touching the walls of the containers housing them. The undercooled metals that result from this process exhibit different characteristics than metals allowed to solidify without interference. These differences can include alterations in the strength and brittleness of the material, giving scientists important clues to understanding the link between structure and processing on Earth and in microgravity. TEMPUS supported 10 materials science investigations on MSL-1. The LIF is a vacuum-heating furnace designed to heat large samples uniformly. On MSL-1, five experiments measuring the diffusion coefficients of a variety of materials, including metals, alloys, and semiconductors, and one investigation

in liquid phase sintering, were conducted using the LIF. For this mission, the furnace was modified to allow ground control of the heating and cooling processes so that researchers could make real-time changes as their investigations progressed.

Media Outreach

The MRPO stepped up its efforts to communicate the results, benefit, and value of microgravity research in FY 1997. Two World Wide Web pages were enhanced to include more frequent updates on microgravity research. Microgravity programmatic and science highlights are captured respectively on <http://microgravity.msfc.nasa.gov/> and <http://science.msfc.nasa.gov/>. These pages exhibit data of interest to the general public and the education community, as well as the microgravity principal investigator community. An increased emphasis has also been placed on communicating the goals and objectives of the MRP by utilizing NASA media outreach campaigns, which consist of news releases for the print media, live television interviews via the NASA satellite, NASA news videos, and continuing microgravity science briefings on NASA television.

4 Microgravity Research Conducted in FY 1997

In fiscal year (FY) 1997, researchers in the Microgravity Research Program's five science disciplines — biotechnology, combustion science, fluid physics, fundamental physics, and materials science — worked to advance human understanding of fundamental physical phenomena and processes through their investigations, which quantify the effects of and overcome the limitations imposed by gravity. Ground-based experiments, coupled with experiments selected for flight definition, comprise a compelling and coherent strategy for understanding and using the microgravity space environment. Highlights of research activity in FY 1997 are presented below.

Biotechnology Overview

Biotechnology is broadly defined as any technology concerned with research on, and manipulation and manufacture of, biological molecules, tissues, and living organisms to produce or obtain products or perform functions. This program uses the microgravity environment to aid in that research. NASA's microgravity biotechnology program is currently active in two major areas: protein crystal growth and mammalian cell and tissue culture. In the former area, researchers seek to grow protein crystals suitable for structural analysis by X-ray diffraction and to understand how these crystals form. In the second area, investigators study and evaluate the benefit of low gravity for growing cells and tissues. NASA's Marshall Space Flight Center in Huntsville, Alabama, is the microgravity biotechnology managing center and provides direct support for research in protein crystal growth. NASA's Johnson Space Center in Houston, Texas, provides support for research in cell and tissue culturing. NASA is also moving ahead with cooperative activities with the National Institutes of Health (NIH) and the Juvenile Diabetes Foundation, as described in the "Program Approach" section of this report.

Funding in biotechnology includes financial support for research centers at the Massachusetts Institute of Technology, Cambridge, Massachusetts; and the Wistar Institute, Philadelphia, Pennsylvania. A cooperative program between NASA and the NIH is continuing for support of research utilizing bioreactor technology at the NIH's Institute for Child Health and Human Development in Bethesda, Maryland. Another cooperative program with the NIH at the NIH's Laboratory for Structural Biology is also continuing. That program is focused on enhancing laboratory-based protein crystallography by improving X-ray diagnostic technology and transferring that technology to the U.S. biotechnology community.

In the area of protein crystal growth, academic, industrial, and federal government researchers, armed with advanced biotechnology techniques and detailed data on the structure of key molecules, are creating a new generation of drugs. Researchers use data on the structure of proteins to design drugs that will interact with specific proteins and treat specific diseases. This approach promises to produce superior drugs for a wide range of conditions, replacing the trial-and-error approach to drug development that has been the rule for centuries. BioCryst (Alabama), Bristol-Myers Squibb (New Jersey), DuPont Merck (Delaware), Eastman Kodak (New York), Eli Lilly (New Jersey),

Schering Plough (New Jersey), Smith Kline Beecham (Pennsylvania), Upjohn (Michigan), and Vertex (Massachusetts) are working with NASA and NASA-funded researchers to produce high-quality protein crystals for new drug development. The first set of such drugs that have resulted from NASA-sponsored research continued to Phase 3 clinical trials — the last set of trials before a new drug can be approved for general use. Although not all drugs successfully complete clinical trials, progression to this stage indicates progress in bringing NASA research results to the general public.

A critical step in drug design is identifying and characterizing the structure of the target molecule. Improving the resolution of protein molecular structures is a difficult process, but it is one that the microgravity environment has been able to advance. This past year has been the best yet in acquiring such critical data. More than 17 of the macromolecules grown in space have revealed information previously unknown regarding their molecular structures. Specific examples of advances in the protein crystal growth area are improved knowledge of the structures of the following proteins:

- **Respiratory Syncytial Virus (RSV)** — an influenza-type virus that produces serious respiratory infections in infants. RSV is responsible for 100,000 to 120,000 hospital admissions per year and approximately 4,000 infant deaths per year in the United States alone.
- **Human Antithrombin III** — a serine protease inhibitor that controls blood coagulation in human plasma. Structural data from the NASA program resulted in the first-ever imaging of the "active loop" of this molecule. These data are crucial to understanding and affecting the function of this molecule.
- **Nucleosome Core Particle and Histone Octamer** — important molecules in fundamental life processes involving the compaction of DNA.
- **Glyceraldehyde-3-Phosphate Dehydrogenase Complex** — a protein used in the development of a drug targeted for treatment of Chagas' disease.

Growing tissue samples — tissue culturing — is one of the fundamental goals of biomedical research. Scientists can use cancer tumors and other tissues successfully grown outside the

body to test and study treatments, like chemotherapy, without risking harm to patients. Tissues from bioreactors will also offer important medical insights into how tissues grow and develop in the body. Other important cell and tissue models under study include promyelocytic leukemia, human mammary tissue for research on breast cancer, pancreatic islet cells for research on diabetes, liver tissue for research on hepatitis, and human bone marrow.

As a result of a NASA Research Announcement and the associated scientific peer review, 36 new investigations were selected and funded in FY 1997. This brings the total active investigator count in biotechnology to more than 80.

Meetings, Awards, and Publications

NASA biotechnology cell science investigators attended and presented at the American Society of Cell Biology meeting in Washington, D.C., in December 1997.

The NASA Biotechnology Protein Crystal Growth Conference was held in Montreal, Canada. This meeting addressed fundamental questions in protein crystallization for both flight- and ground-based experiments and provided an international forum for discussion of research and research direction.

The NASA biotechnology cell science investigators working group meeting was held in Houston, Texas, to discuss results from the previous year's research. Over 100 scientists attended.

Research performed in biotechnology cell science was considered of such importance that the entire May 1997 issue of *In Vitro Cellular and Developmental Biology* was dedicated to this work. Twelve manuscripts were included in that issue.

Two patents and one licensing agreement were awarded to scientists in the program this year.

Lawrence DeLucas, of the Center for Macromolecular Crystal Growth, received the NASA Public Service Medal for his contributions to NASA and the nation.

Flight Experiments

The NASA/*Mir* program once again hosted a long-duration biotechnology cell science payload. The Biotechnology Specimen Temperature Controller, a permanent part of the Biotechnology System on the Russian space station, *Mir*, supported research from three different research teams. Included were studies in neuroendocrine cells by Peter Lelkes, of the University of Wisconsin Medical School; studies on renal tubular cells by Timothy Hammond, of Tulane University; and studies on promyelocytic leukemia cells by Neal Pellis and Thomas Goodwin, of Johnson Space Center. While flights to *Mir* are primarily designed to develop and validate new technologies in preparation for the International Space Station, scientific studies, such as these, have also been performed during those validations.

Results from these experiments are still pending, as the long-duration increment continues well into 1998.

J. Milburn Jessup, of the University of Pittsburgh Medical Center, was able to refile his investigation of the growth of MIP-101 colon carcinoma cells in order to confirm the previous results. This additional information will enable the publication of his results in a major scientific journal. Growth of such colon cancer cells and tissue allows the formulation of tumor models that are valuable in understanding the dynamic interactions that result in tumor growth and in establishing novel therapeutic strategies.

The protein crystal growth program flew 13 instruments during FY 1997. Those instruments contained more than 3,000 individual samples of a total of 51 different proteins. Evaluation of the results from these flights is in varying stages, depending on the flight date. Structural data returned from these flights will be used to begin or augment the process of drug design. Seventeen improvements in molecular structure were realized in FY 1997.

The FY 1997 biotechnology ground and flight tasks are listed in **Table 3**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Table 3 **Biotechnology tasks funded by the Microgravity Research Division in FY 1997**
(includes some continuing projects at no additional cost)

Flight Experiments

Protein Crystal Growth Vapor-Diffusion Flight Hardware and Facility
Daniel C. Carter
New Century Pharmaceuticals, Inc., Huntsville, AL

Protein Crystal Growth in Microgravity
Lawrence J. DeLucas
University of Alabama, Birmingham, Birmingham, AL

Electrophoretic Separation of Cells and Particles From Rat Pituitary
Wesley C. Hymer
Pennsylvania State University, University Park, PA

Growth, Metabolism, and Differentiation of MIP-101 Carcinoma Cells
J. Milburn Jessup
University of Pittsburgh Medical Center, Pittsburgh, PA

Membrane Transport Phenomena
Larry W. Mason
Lockheed Martin Astronautics, Denver, CO

Enhanced Dewar Program
Alexander McPherson, Jr.
University of California, Irvine, Irvine, CA

An Observable Protein Crystal Growth Flight Apparatus
Alexander McPherson, Jr.
University of California, Irvine, Irvine, CA

Investigation of Protein Crystal Growth Mechanisms in Microgravity
Keith B. Ward
Naval Research Laboratory, Washington, DC

Ground-Based Experiments

Experimental Assessment of Multicomponent Effects in Diffusion-Dominated Transport in Protein Crystal Growth and Electrophoresis and Chiral Separations
John G. Albright
Texas Christian University, Fort Worth, TX

Crystallization Mechanisms of Membrane Proteins
James P. Allen
Arizona State University, Tempe, AZ

Novel Concepts in Acoustophoresis for Biotechnology Applications
Robert E. Apfel
Yale University, New Haven, CT

Real-Time Monitoring of Protein Concentration in Solution to Control Nucleation and Crystal Growth
Mark Arnold
University of Iowa, Iowa City, IA

The Use of Bioactive Glass Particles as Microcarriers in Microgravity Environments
Portonovo S. Ayyaswamy
University of Pennsylvania, Philadelphia, PA

Protein Crystal-Based Nanomaterials
Jeffrey A. Bell
Rensselaer Polytechnic Institute, Troy, NY

Expansion and Differentiation of Cells in Three-Dimensional Matrices Mimicking Physiological Environments
Rajendra S. Bhatnagar
University of California, San Francisco, San Francisco, CA

Searching for the Best Protein Crystals: Synchrotron-Based Mosaicity Measurements of Crystal Quality and Theoretical Modeling
Gloria Borgstahl
University of Toledo, Toledo, OH

Development of an Insulin-Secreting, Immunoprivileged Cell-Cell Aggregate Utilizing the NASA Rotating Wall Vessel
Donald F. Cameron
University of South Florida, College of Medicine, Tampa, FL

Quantitative, Statistical Methods for Preflight Optimization and Postflight Evaluation of Macromolecular Crystal Growth
Charles W. Carter
University of North Carolina, Chapel Hill, Chapel Hill, NC

Origin of Imperfections in Growing Protein Crystals by *In-Situ* Rocking Curve Analysis
Alexander A. Chernov
Universities Space Research Association,
Marshall Space Flight Center, Huntsville, AL

Infrared Signatures for Mammalian Cells in Culture
Krishnan K. Chittur
University of Alabama, Huntsville, Huntsville, AL

Microgravity-Simulated Prostate Cell Culture
Leland W. K. Chung
University of Virginia, Charlottesville, VA

Noninvasive Near-Infrared Sensor for Continual Cell Glucose Measurement
Gerard L. Cote
Texas A&M University, College Station, TX

A Comprehensive Investigation of Macromolecular Transport During Protein Crystallization
Lawrence J. DeLucas
University of Alabama, Birmingham, Birmingham, AL

Development of Robotic Techniques for Microgravity Protein Crystal Growth
Lawrence J. DeLucas
University of Alabama, Birmingham, Birmingham, AL

Macromolecular Crystallization: Physical Principles, Passive Devices, and Optimal Protocols
George T. DeTitta
Hauptman-Woodward Medical Research Institute, Buffalo, NY

The Effect of Microgravity on the Human Skin Equivalent
S. Dan Dimitrijevic
University of North Texas Health Science Center, Fort Worth, TX

Use of Microgravity-Based Bioreactors to Study Intercellular Communication in Airway Cells
Ellen R. Dirksen
University of California, Los Angeles, Los Angeles, CA

Microgravity Thresholds for Anti-Cancer Drug Production on Conifer Cells
Don J. Durzan
University of California, Davis, Davis, CA

Laser Scattering Tomography for the Study of Defects in Protein Crystals
Robert S. Feigelson
Stanford University, Stanford, CA

Role of Fluid Shear on Three-Dimensional Bone Tissue Culture
John A. Frangos
University of California, San Diego, La Jolla, CA

Microgravity Tissue Engineering

Lisa E. Freed
Massachusetts Institute of Technology, Cambridge, MA

Epitaxial Growth of Protein Crystals on Self-Assembled Monolayers

Jonathan M. Friedman
University of Houston, Houston, TX

Protein and DNA Crystal Lattice Engineering

D. Travis Gallagher
Center for Advanced Research in Biotechnology, Rockville, MD

Microgravity-Based Three-Dimensional Transgenic Cell Models

Steve R. Gonda
Johnson Space Center, Houston, TX

Lymphocyte Invasion Into Tumor Models Emulated Under Microgravity Conditions *In Vitro*

Thomas J. Goodwin
Johnson Space Center, Houston, TX

Application of Bioreactor Technology for Analysis and Countermeasure Development of Microgravity-Induced Suppression of Innate Immunity

Elizabeth A. Grimm
University of Texas M. D. Anderson Cancer Center, Houston, TX

Differentiation of Cultured Normal Human Renal Epithelial Cells in Microgravity

Timothy G. Hammond
Tulane University Medical Center, New Orleans, LA

Production of 1-25-diOH D3 by Renal Epithelial Cells in Simulated Microgravity Culture

Timothy G. Hammond
Tulane University Medical Center, New Orleans, LA

Excitable Cells and Growth Factors Under Microgravity Conditions

Charles R. Hartzell
Alfred I. DuPont Institute of the Nemours Foundation, Wilmington, DE

Determining the Conditions Necessary for the Development of Functional Replacement Cartilage Using a Microgravity Reactor

Carole A. Heath
Iowa State University, Ames, IA

Self-Assembly of Hepatocyte Spheroids in Microgravity

Wei-Shou Hu
University of Minnesota, Minneapolis, MN

The Effects of Microgravity on Viral Replication

John H. Hughes
Ohio State University, Columbus, OH

Three-Dimensional Tissue Interactions in Colorectal Cancer Metastasis

J. Milburn Jessup
University of Pittsburgh Medical Center, Pittsburgh, PA

Use of NASA Bioreactor to Study Cell Cycle Regulation

J. Milburn Jessup
University of Pittsburgh Medical Center, Pittsburgh, PA

Use of Rotating Wall Vessel to Facilitate Culture of Norwalk Virus

Philip Johnson
University of Texas Medical School, Houston, Houston, TX

Protein Crystallization in Complex Fluids

Eric W. Kaler
University of Delaware, Newark, DE

Fibril Formation by Alzheimer's Disease Amyloid in Microgravity

Daniel A. Kirschner
Boston College, Chestnut Hill, MA

Applications of Atomic Force Microscopy to Investigate Mechanisms of Protein Crystal Growth

John H. Konnert
Naval Research Laboratory, Washington, DC

Regulation of Skeletal Muscle Development and Differentiation *In Vitro* by Mechanical and Chemical Factors

William E. Kraus
Duke University Medical Center, Durham, NC

Multidisciplinary Studies of Cells, Tissues, and Mammalian Development in Simulated Microgravity

Elliot M. Levine
Wistar Institute, Philadelphia, PA

Analysis of Electrophoretic Transport of Macromolecules Using Pulsed Field Gradient NMR

Bruce R. Locke
Florida State University, Tallahassee, FL

Quantitative Analysis of Surfactant Interactions During Membrane Protein Crystallization

Patrick J. Loll
University of Pennsylvania School of Medicine, Philadelphia, PA

Ground-Based Program for the Physical Analysis of Macromolecular Crystal Growth

Alexander J. Malkin
University of California, Riverside, Riverside, CA

Thyroid Follicle Formation in Microgravity: Three-Dimensional Organoid Construction in a Low-Shear Environment

Andreas Martin
Mount Sinai Medical Center, New York, NY

Biological Particle Separation in Low Gravity

D. James Morr e
Purdue University, West Lafayette, IN

Continuous, Noninvasive Monitoring of Rotating Wall Vessels and Application to the Study of Prostate Cancer

David W. Murhammer
University of Iowa, Iowa City, IA

Diffusion, Viscosity, and Crystal Growth of Proteins in Microgravity

Allan S. Myerson
Polytechnic University, Brooklyn, NY

Insect Cell Cultivation in Simulated Microgravity

Kim O'Connor
Tulane University, New Orleans, LA

Shear Sensitivities of Human Bone Marrow Cultures

Bernhard O. Palsson
University of California, San Diego, La Jolla, CA

Microgravity and Immunosuppression: A Ground-Based Model in the Slow-Turning Lateral Vessel Bioreactor

Neal R. Pellis
Johnson Space Center, Houston, TX

Fluorescence Studies of Protein Aggregation in Under- and Oversaturated Solutions

Marc L. Pusey
Marshall Space Flight Center, Huntsville, AL

Isolation of the Flow, Growth and Nucleation Rate, and Microgravity Effects on Protein Crystal Growth

Marc L. Pusey
Marshall Space Flight Center, Huntsville, AL

Stem Cell Expansion in Rotating Bioreactors

Peter J. Quesenberry
University of Massachusetts Medical Center, Worcester, MA

Study of Crystallization and Solution Properties of Redesigned Protein Surfaces

David C. Richardson
Duke University Medical Center, Durham, NC

Heterozygous Ataxia-Telangiectasia Human Mammary Cells as a Microgravity-Based Model of Differentiation and Cancer Susceptibility

Robert C. Richmond
Dartmouth-Hitchcock Medical Center, Lebanon, NH

Nucleation and Convection Effects in Protein Crystal Growth

Franz E. Rosenberger
University of Alabama, Huntsville, Huntsville, AL

Protein-Precipitant-Specific Criteria for the Impact of Reduced Gravity on Crystal Perfection

Franz E. Rosenberger
University of Alabama, Huntsville, Huntsville, AL

Enhancement of Cell Function in Culture by Controlled Aggregation Under Microgravity Conditions

W. Mark Saltzman
Cornell University, Ithaca, NY

Use of NASA Bioreactors in a Novel Scheme for Immunization Against Cancer

Cherylyn A. Savary
University of Texas M. D. Anderson Cancer Center, Houston, TX

Electrohydrodynamics of Suspensions

Dudley A. Saville
Princeton University, Princeton, NJ

Microgravity and the Biology of Neural Stem Cells

William J. Schwartz
University of Massachusetts Medical School, Worcester, MA

Robotic Acquisition and Cryogenic Preservation of Single Crystals of Macromolecules for X-Ray Diffraction

Craig D. Smith
University of Alabama, Birmingham, Birmingham, AL

Gastric Mucosal Cell Culture in Simulated Microgravity

Adam J. Smolka
Medical University of South Carolina, Charleston, SC

Influence of Microgravity Conditions on Gene Transfer Into Expanded Populations of Human Hematopoietic Stem Cells

F. Marc Stewart
University of Massachusetts Medical Center, Worcester, MA

Production of Recombinant Human Erythropoietin by Mammalian Cells Cultured in Simulated Microgravity

Arthur J. Sytkowski
Beth Israel Deaconess Medical Center, Boston, MA

Defects, Growth, and Elastic Properties of Protein Crystals

Robert E. Thorne
Cornell University, Ithaca, NY

Mechanisms for Membrane Protein Crystallization: Analysis by Small-Angle Neutron Scattering

David M. Tiede
Argonne National Laboratory, Argonne, IL

Preparation and Analysis of RNA Crystals

Paul Todd
University of Colorado, Boulder, Boulder, CO

Development of Microflow Biochemical Sensors for Space Biotechnology

Bruce Towe
Arizona State University, Tempe, AZ

Experimental Studies of Protein Crystal Growth Under Simulated Low-Gravity Conditions

Eugene H. Trinh
Jet Propulsion Laboratory, Pasadena, CA

Two-Dimensional Protein Crystallization at Interfaces

Viola Vogel
University of Washington, Seattle, WA

Two-Dimensional Crystal Growth in Microgravity

Theodore G. Wensel
Baylor College of Medicine, Houston, TX

Thermal Optimization of Growth and Quality of Protein Crystals

John M. Wiencek
University of Iowa, Iowa City, IA

Thermodynamics of Protein Crystallization and Links to Crystal Quality

John M. Wiencek
University of Iowa, Iowa City, IA

Metastable Solution Structure and Optimization Strategies in Protein Crystal Growth

Lori J. Wilson
East Tennessee State University, Johnson City, TN

A Rational Approach for Predicting Protein Crystallization

W. William Wilson
Mississippi State University, Mississippi State, MS

Search for a Dilute Solution Property to Predict Protein Crystallization

W. William Wilson
Mississippi State University, Mississippi State, MS

Novel Microgravity Optical Technique for Molecularly Engineering Electrophoretic Media

Denis Wirtz
Johns Hopkins University, Baltimore, MD

The Effects of Microgravity/Low Shear on Glycosylation and Eukaryotic DNA Virus Replication

H. Alan Wood
Cornell University, Ithaca, NY

Ex-Vivo Hemopoieses in a Three-Dimensional Human Bone Marrow Culture Under Simulated Microgravity

J. H. David Wu
University of Rochester, Rochester, NY

Liver Tissue Engineering in a Microgravity Environment

Boris Yoffe
Baylor College of Medicine, Houston, TX

Characterization of Solvation Potentials Between Small Particles

Charles F. Zukoski
University of Illinois, Urbana-Champaign, Urbana, IL

Particle Interaction Potentials and Protein Crystal Quality

Charles F. Zukoski
University of Illinois, Urbana-Champaign, Urbana, IL

Combustion Science Overview

Combustion and the results of combustion processes affect each of us every day. Combustion is responsible for the majority of the world's electric power production, home heating, and ground and air transportation. Combustion by-products are major contributors to air pollution and global warming. Additionally, unintentional fires claim thousands of lives and cost billions of dollars in property damage. Beneficial control of combustion is impeded by a lack of fundamental understanding of combustion processes. Combustion research is hampered by the effects of gravitational forces more than other areas of science, since combustion intrinsically involves production of high-temperature gases in which low densities trigger buoyant flows. These flows cause the reaction zone to collapse into very thin sheet-like regions that are impenetrable by current or anticipated instrumentation. Conducting experiments in microgravity eliminates buoyancy and expands the reaction zone to the extent that measurements can be made. The resulting data are used to verify combustion theory, validate numerical models, and develop fresh insight into elemental phenomena, all of which can be applied to Earth-based combustion processes.

Specific potential benefits that may ensue, in part, from microgravity combustion research include the following:

- Increased conversion efficiency of chemical energy stored in fuels to useful heat and work in combustion devices, leading to economic savings, reduced dissipation of scarce fuel reserves, and lower greenhouse gas emissions.
- Reduction of combustion-related effluents that pollute the atmosphere.
- Reduction of fire and explosion hazards.
- Improved hazardous waste incineration processes.
- Development of improved materials via combustion synthesis for use in widely diverse applications such as bone replacement, electrical components, and engines.

The microgravity combustion science program, in conjunction with the combustion science discipline working group, has defined the following high priority areas for microgravity research and is supporting research in each area:

Combustion-turbulence interactions: Virtually all practical combustion devices, except gas stoves, involve turbulent flows. Microgravity uniquely limits the range of turbulent length and time scales to those large enough to be tractable experimentally.

Soot processes: Soot is a critical element in many combustion systems, strongly affecting combustor lifetime, efficiency, peak power output, and pollution generation. The lack of buoyancy-induced accelerated flows in a microgravity environment results in longer residence times to investigate primary soot formation, soot clustering, cluster-cluster agglomeration, and oxidation.

Diagnostics: Technological improvements in measurement are a mandate due to historic and valid criticism of the qualitative

nature of early microgravity experiments and, more importantly, due to benefits for active control of combustors.

Pressure effects: High pressure and/or supercritical operation of combustors yields improved thermodynamic efficiency at the expense of increased pollutant generation. Conventional diesel engines operate at 50 atmospheres (atm), but most research has been conducted at near ambient conditions (1 atm). The influence of buoyancy increases with pressure.

Benchmark data on laminar flames: Practical devices, although highly turbulent, operate in the “laminar flamelet” regime. As such, improvements in understanding laminar flame structure and associated characteristics have a direct impact on turbulence modeling.

Spray and aerosol cloud combustion: This type of combustion accounts for 25 percent of the world's energy use yet remains poorly understood from both fundamental and practical perspectives. Microgravity not only offers a quiescent, nonbuoyant environment, it also overcomes the problem of droplet settling in a 1g environment.

Combustion synthesis: Flame-synthesized products include valuable vapors (e.g., acetylene), ultrafine particles (e.g., fullerenes, silicon oxides, titanium oxides), coatings (e.g., diamonds), and monolithic solids (e.g., boron carbide, titanium boride). These materials are rapidly expanding in breadth of use and value, but production remains very much an art, rather than a science. Sedimentation and buoyant plumes lead to short residence times and interfere with investigation into the mechanisms of material production. Current research is geared toward interpreting the differences between normal- and low-gravity processing and improvement of the product.

Surface flame spread: Large-scale fires and fire spread on Earth are complicated by buoyancy-fed turbulent processes and thermal radioactive interactions with surrounding materials, terrain, and building structures. Current models of flame spread generally omit thermal radiation because of the weakness in understanding this transport mechanism. Laboratory-scale experiments in microgravity have begun to elucidate the importance of thermal radiation and indicate that these results might be utilized in modeling large-scale fires.

Transient processes in gaseous flames: Microgravity experimentation can provide insights into flame instabilities, such as ignition, extinction, and imposed perturbations that are often masked by buoyancy in normal gravity.

Spacecraft fire safety: Models used to study spacecraft fire safety are still considered “primitive.” Further research is required in the areas of microgravity flammability, fire spread, fire and smoke detection, fire suppression, and postfire cleanup.

Partial-gravity combustion: Combustion issues on the surfaces of the Moon and Mars will include habitat fire safety, waste incineration, roving vehicle power, and propellant storage safety.

Meetings, Awards, and Publications

The fourth International Microgravity Combustion Workshop was held in Cleveland, Ohio, May 19–21, 1997. Attendance at the workshop reached a new record of 264 registrants. There were 89 technical presentations and 3 plenary/programmatic presentations; proceedings were distributed at the conference.

Chung Law, of Princeton University, was selected to receive the prestigious American Society of Mechanical Engineers Heat Transfer Memorial Award in Science. The award read, in part, “for outstanding contributions to heat and mass transfer in chemically reacting systems, especially on droplet and spray combustion, flame structure and dynamics, and boundary-layer combustion.” Law, principal investigator (PI) for the Studies of Flame Structure in Microgravity investigation, gave special thanks to the microgravity combustion science program for its support of the work leading to this award.

A paper titled “Quantitative Rainbow Schlieren Deflectometry” by Paul Greenberg, Robert Klimek, and Donald R. Buchele was selected as the NASA Lewis Distinguished Scientific Publication of the Year. The paper was published in *Applied Optics*.

Flight Experiments

Fiscal year (FY) 1997 was a banner year for microgravity combustion science flight experiments. For the second consecutive year, successful flight investigations were conducted in half the research topic areas and on all available carriers. Additionally, the first multiuser combustion facility, Combustion Module-1 (CM-1), demonstrated design concepts and operation techniques that are essential to conducting operations on the International Space Station (ISS).

The first Microgravity Science Laboratory (MSL-1) mission flew twice in 1997. Although the first flight in April was cut short due to an orbiter fuel cell problem, three of the four combustion investigations were operated and all produced publishable data. After an unprecedented turnaround, the mission reflown in July as MSL-1R; over 100 fires were set and studied during the reflight.

The Laminar Soot Processes (LSP) and the Structure of Flame Balls at Low Lewis Number (SOFBALL) investigations were conducted in the CM-1. CM-1, which is described in more detail in the “Hardware” section of this report, provided common laboratory services, such as data processing/storage, command/communications, containment, and gas management/cleanup to both investigations. The specific apparatus for each investigation was easily integrated with CM-1 as an on-orbit procedure. This type of operation is prototypical of the way combustion science will be conducted in the Fluids and Combustion Facility on the ISS.

The LSP experiment provided observations of soot processes within nonbuoyant, nonpremixed flames that are relevant to practical combustion in aircraft propulsion systems, diesel engines, and furnaces, but with the flames slowed and spread out to allow measurements that are not tractable within the practical flames. Initial analysis of the new measurements suggest the existence of

universal relationships between soot processes and the degree of mixing within nonbuoyant flames. These relationships are known as the soot paradigm, a controversial hypothesis based upon indirect observations of practical nonbuoyant flames. If the paradigm proves to be true, it offers simplified ways to control and model soot processes in practical flames. The new measurements yielded the first-ever observations of steady, soot-containing, nonbuoyant flames both with and without soot emissions. These flames provided textbook examples of soot formation processes in practical flames that are invaluable for developing methods for controlling the emissions of pollutant soot.

SOFBALL explores the behavior of newly discovered flame phenomena called “flame balls.” These spherical, stable, stationary flame structures, observed only in microgravity, provide a unique opportunity to study the interactions of the two most important processes necessary for combustion (chemical reaction, and heat and mass transport) in the simplest possible configuration. The preliminary data obtained during the test runs result in the following conclusions:

- Steady, nearly stationary flame balls exist in an extended-duration microgravity environment.
- The extended length of the burns verifies the theoretical predictions that these flames evolve on a very slow time scale, on the order of hundreds of seconds.
- The flame balls are sensitive to orbiter thruster firings above 50 micro-g seconds. During free drift periods, the flame balls were nearly motionless for many minutes, while the flame balls moved slightly after vernier thruster firings or water dumps.
- All the flame balls, regardless of the inert component, number of flame balls, or pressure, produced 1 to 1.8 watts of radiant power, in disagreement with premission predictions.

The Droplet Combustion Experiment (DCE) is designed to investigate the combustion aspects of single, isolated droplets under different pressures and ambient oxygen concentrations for a range of droplet sizes varying between 2 and 5 mm. The DCE runs during the MSL-1 mission identified three regimes of droplet combustion. In addition to the well-known quasisteady regime, in which the squares of both droplet and flame diameters decrease linearly with time and diffusive extinction of the flames occurs when the droplet becomes sufficiently small, two previously undocumented regimes were discovered. For sufficiently large droplets, there is a regime of radiative extinction in which energy loss by emission of infrared radiation causes flame extinction during the initial stage of flame expansion, leaving a large fuel droplet that slowly vaporizes in the hot gases left behind after combustion has ceased. At sufficiently high oxygen content, there is a regime of droplet disappearance in which the flame persists in an outer transient region after the droplet has vaporized completely. This flame rapidly contracts at the end of the burn, extinguishing diffusively at a nonzero flame radius.

The Fiber-Supported Droplet Combustion (FSDC-2) experiment studied fundamental phenomena related to liquid fuel droplet combustion in air. Pure fuels and mixtures of fuels were burned as isolated single and duo droplets with and without forced air convection. The FSDC-2 investigation was conducted in the Microgravity Glovebox facility of the shuttle's Spacelab during MSL-1R.

Four sounding rocket flights were conducted in FY 1997. The Diffusive and Radiative Transport in Fires (DARTFire) experiment completed its final three flights to investigate flame initiation, fire spread, and postsread steady-state combustion of a thick solid-fuel sample under various low-speed oxidizer flows. Small amounts of radiant heating were imposed on the fuel samples to determine the effects of this kind of assisted heating of the fuel sample on flame survivability and spread. DARTFire marks the first experimental control and measurement of radiative heating in a microgravity combustion experiment. The imposed radiative heating is realistic in the sense that nearby burning material provides radiant heating in both practical and accidental fires.

The fourth sounding rocket flight for the Spread Across Liquids (SAL) investigation occurred on September 10, within 30 minutes of the final DARTFire launch. This dual launch saved range costs. SAL-4 continued the investigation of flame spread over a long, deep pool of liquid fuel in an extended-duration, low-gravity environment. In SAL-4, gas-phase flow visualization

was attempted for the first time, and the smoke tracing systems performed perfectly. The gas-phase recirculation cell ahead of the spreading flame could be observed throughout the full fields of view of every planned camera view, as well as the schlieren view. Visualization of the vortex by the smoke tracer was sufficiently high in resolution that rotation rates of the vortex in the cell can be calculated.

The Solid Surface Combustion Experiment flew for the ninth time on the 85th Space Transportation System (STS-85) mission. This flight investigated the behavior of a long, flat polymethyl methacrylate (PMMA) sample ignited in the "near extinction" atmosphere of 50 percent oxygen and 50 percent nitrogen at 1 atm of pressure. The objective of this experiment was to test the theory that flame spread over thick fuel samples is inherently unsteady in quiescent environments. In flight, the PMMA sample ignited normally with a flame that spread at a gradually slower rate. The flame eventually stopped spreading, receded, then quenched. This behavior, never before observed experimentally, was predicted by the PI's model.

The FY 1997 ground and flight tasks for combustion science are listed in **Table 4**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Table 4 **Combustion science tasks funded by the Microgravity Research Division in FY 1997**
(includes some continuing projects at no additional cost)

Flight Experiments

Low-Velocity, Opposed-Flow Flame Spread in a Transport-Controlled Microgravity Environment

Robert A. Altenkirch
Washington State University, Pullman, WA

Reflight of the Solid-Surface Combustion Experiment With Emphasis on Flame Radiation Near Extinction

Robert A. Altenkirch
Washington State University, Pullman, WA

Scientific Support for an Orbiter Middeck Experiment on Solid-Surface Combustion

Robert A. Altenkirch
Washington State University, Pullman, WA

Gravitational Effects on Laminar, Transitional, and Turbulent Gas-Jet Diffusion Flames

M. Yousef Bahadori
Science Applications International Corp., Torrance, CA

Sooting and Radiation Effects in Droplet Combustion

Mun Young Choi
University of Illinois, Chicago, Chicago, IL

Candle Flames in Microgravity

Daniel L. Dietrich
Lewis Research Center, Cleveland, OH

Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames

Gerard M. Faeth
University of Michigan, Ann Arbor, MI

Unsteady Diffusion Flames: Ignition, Travel, and Burnout

Frank Fendell
TRW Space and Electronics Group, Redondo Beach, CA

Flammability Diagrams of Combustible Materials in Microgravity

A. Carlos Fernandez-Pello
University of California, Berkeley, Berkeley, CA

Fundamental Study of Smoldering Combustion in Microgravity

A. Carlos Fernandez-Pello
University of California, Berkeley, Berkeley, CA

Ignition and the Subsequent Transition to Flame Spread in Microgravity

Takashi Kashiwagi
National Institute of Standards and Technology, Gaithersburg, MD

The High Lewis Number Diffusive-Thermal Instability in Premixed Gas Combustion and Low-Temperature Hydrocarbon Oxidation and Cool Flames

Howard G. Pearlman
Lewis Research Center, Cleveland, OH

Studies of Premixed Laminar and Turbulent Flames at Microgravity

Paul D. Ronney
University of Southern California, Los Angeles, CA

Ignition and Flame Spread of Liquid Fuel Pools

Howard D. Ross
Lewis Research Center, Cleveland, OH

Combustion Experiments in Reduced Gravity With Two-Component Miscible Droplets

Benjamin D. Shaw
University of California, Davis, Davis, CA

Combustion of Solid Fuel in Very Low Speed Oxygen Streams

James S. T'ien
Case Western Reserve University, Cleveland, OH

Droplet Combustion Experiment

Forman A. Williams
University of California, San Diego, La Jolla, CA

Ground-Based Experiments

Effects of Energy Release on Near-Field Flow Structure of Gas Jets

Ajay K. Agrawal
University of Oklahoma, Norman, OK

Radiant Extinction of Gaseous Diffusion Flames

Arvind Atreya
University of Michigan, Ann Arbor, MI

Multicomponent Droplet Combustion in Microgravity: Soot Formation, Emulsions, Metal-Based Additives, and the Effect of Initial Droplet Diameter

C. Thomas Avedisian
Cornell University, Ithaca, NY

Gas-Phase Combustion Synthesis of Metal and Ceramic Nanoparticles

Richard L. Axelbaum
Washington University, St. Louis, MO

Ignition and Combustion of Bulk Metals in Microgravity

Melvyn C. Branch
University of Colorado, Boulder, Boulder, CO

Modeling of Microgravity Combustion Experiments — Phase II

John D. Buckmaster
University of Illinois, Urbana-Champaign, Urbana, IL

A Numerical Model for Combustion of Bubbling Thermoplastic Materials in Microgravity

Kathryn M. Butler
National Institute of Standards and Technology, Gaithersburg, MD

Heterogeneous Combustion of Porous Solid-Fuel Particles Under Microgravity: A Comprehensive, Theoretical, and Experimental Study

H. K. Chelliah
University of Virginia, Charlottesville, VA

Buoyancy Effects on the Structure and Stability of Burke-Schumann Diffusion Flames

L.-D. Chen
University of Iowa, Iowa City, IA

Gravitational Effects on Premixed Turbulent Flames: Microgravity Flame Structures

Robert K. Cheng
Lawrence Berkeley Laboratory, Berkeley, CA

Combustion of Interacting Droplet Arrays in a Microgravity Environment

Daniel L. Dietrich
Lewis Research Center, Cleveland, OH

Interaction of Burning Metal Particles

Edward L. Dreizin
AeroChem Research Laboratory, The Titan Corp., Princeton, NJ

Internal and Surface Phenomena in Heterogeneous Metal Combustion

Edward L. Dreizin
AeroChem Research Laboratory, The Titan Corp., Princeton, NJ

Flame-Vortex Interactions Imaged in Microgravity

James F. Driscoll
University of Michigan, Ann Arbor, MI

Aerodynamic, Unsteady, Kinetic, and Heat Loss Effects on the Dynamics and Structure of Weakly Burning Flames in Microgravity

Fokion N. Egolfopoulos
University of Southern California, Los Angeles, CA

Detailed Studies on the Structure and Dynamics of Reacting Dusty Flows at Normal and Microgravity

Fokion N. Egolfopoulos
University of Southern California, Los Angeles, CA

Effects of Gravity on Sheared and Nonsheared Turbulent, Nonpremixed Flames

Said E. Elghobashi
University of California, Irvine, Irvine, CA

Soot Processes in Freely Propagating Laminar Premixed Flames

Gerard M. Faeth
University of Michigan, Ann Arbor, MI

Combustion of Electrostatic Sprays of Liquid Fuels in Laminar and Turbulent Regimes

Alessandro Gomez
Yale University, New Haven, CT

Characteristics of Nonpremixed, Turbulent Flames in Microgravity

Uday Hegde
NYMA, Inc., Cleveland, OH

Three-Dimensional Flow in a Microgravity Diffusion Flame

Jean R. Hertzberg
University of Colorado, Boulder, Boulder, CO

Combustion Synthesis of Fullerenes and Fullerene Nanostructures in Microgravity

Jack B. Howard
Massachusetts Institute of Technology, Cambridge, MA

Unsteady Numerical Simulations of the Stability and Dynamics of Flames in Microgravity

K. Kailasanath
Naval Research Laboratory, Washington, DC

Real-Time, Quantitative, Three-Dimensional Imaging of Diffusion Flame Species

Daniel J. Kane
Southwest Sciences, Inc., Santa Fe, NM

Soot and Radiation Measurements in Microgravity Turbulent Jet Diffusion Flames

Jerry C. Ku
Wayne State University, Detroit, MI

Studies of Flame Structure in Microgravity

Chung K. Law
Princeton University, Princeton, NJ

Chemical Inhibitor Effects on Diffusion Flames in Microgravity

Gregory T. Linteris
National Institute of Standards and Technology, Gaithersburg, MD

Computational and Experimental Study of Laminar Diffusion Flames in a Microgravity Environment

Marshall B. Long
Yale University, New Haven, CT

Dynamics of Liquid Propellant Combustion at Reduced Gravity

Stephen B. Margolis
Sandia National Laboratories, Livermore, CA

Structure and Dynamics of Diffusion Flames in Microgravity

Moshe Matalon
Northwestern University, Evanston, IL

Filtration Combustion for Microgravity Applications: Smoldering, and Combustion Synthesis of Advanced Materials

Bernard J. Matkowsky
Northwestern University, Evanston, IL

Combustion of PTFE: The Effect of Gravity on Ultrafine Particle Generation

J. Thomas McKinnon
Colorado School of Mines, Golden, CO

Premixed Turbulent Flame Propagation in Microgravity

Suresh Menon
Georgia Institute of Technology, Atlanta, GA

Gravitational Influences on Flame Propagation Through Nonuniform Premixed Gas Systems

Fletcher J. Miller
Lewis Research Center, Cleveland, OH

A Fundamental Study of the Combustion Syntheses of Ceramic-Metal Composite Materials Under Microgravity Conditions — Phase II

John J. Moore
Colorado School of Mines, Golden, CO

Stretched Diffusion Flames in Von Karman Swirling Flows

Vedha Nayagam
Analex Corporation, Brook Park, OH

Flammability Limits and Flame Dynamics of Spherical Flames in Homogeneous and Heterogeneous Mixtures

Paul D. Ronney
University of Southern California, Los Angeles, CA

Flow and Ambient Atmosphere Effects on Flame Spread at Microgravity

Paul D. Ronney
University of Southern California, Los Angeles, CA

Combustion of Unconfined Droplet Clusters in Microgravity

Gary A. Ruff
Drexel University, Philadelphia, PA

Quantitative Measurement of Molecular Oxygen in Microgravity Combustion

Joel A. Silver
Southwest Sciences, Inc., Santa Fe, NM

Numerical Modeling of Flame Balls in Fuel-Air Mixtures

Mitchell D. Smooke
Yale University, New Haven, CT

Combustion of Rotating, Spherical, Premixed, and Diffusion Flames in Microgravity

Siavash H. Sohrab
Northwestern University, Evanston, IL

Diffusion Flame Structure, Shape, and Extinction: Geometrical Considerations

Jose L. Torero
University of Maryland, College Park, College Park, MD

Interactions Between Flames on Parallel Solid Surfaces

David L. Urban
Lewis Research Center, Cleveland, OH

Gasless Combustion Synthesis From Elements Under Microgravity: A Study of Structure-Formation Processes

Arvind Varma
University of Notre Dame, Notre Dame, IN

Studies of Wind-Aided Flame Spread Over Thin Cellulosic Fuels in Microgravity

Indrek S. Wichman
Michigan State University, East Lansing, MI

High-Pressure Combustion of Binary Fuel Sprays

Forman A. Williams
University of California, San Diego, La Jolla, CA

Laser Diagnostics for Fundamental Microgravity Droplet Combustion Studies

Michael Winter
United Technologies Research Center, East Hartford, CT

Combustion of a Polymer (PMMA) Sphere in Microgravity

Jiann C. Yang
National Institute of Standards and Technology, Gaithersburg, MD

Fluid Physics Overview

Fluid physics is the study of the motion of fluids and the effects of such motion. Since three of the four states of matter (gas, liquid, and plasma) are fluid, and even the fourth (solid) behaves like a fluid under many conditions, fluid physics encompasses a wide spectrum of industrial, as well as natural, processes and phenomena. Fluid motions are responsible for most transport and mixing that take place in the environment, in industrial processes, in vehicles, and in living organisms. The ultimate goal of research in fluid physics is to improve our ability to predict and control the behavior of fluids in all of the above instances, so as to improve our ability to design devices and operate them. Fluid motion in most situations is strongly influenced by gravity. The low-gravity environment of space offers a powerful research tool for the study of fluid physics, enabling the observation and control of fluid phenomena in ways not possible on Earth. Experiments conducted in this environment have clearly demonstrated the value of microgravity by revealing results that are either completely unexpected or unobservable in Earth's gravitational field. These results are providing new insight into the behavior of fluids in terrestrial environments.

The microgravity fluid physics program currently has four major research areas: complex fluids, interfacial phenomena, dynamics and instabilities, and multiphase flows and phase change. There are 71 ground-based and 20 flight/flight definition principal investigators (PIs) conducting experimental research as well as developing the theoretical framework for understanding the effects of gravity on processes involving fluids. Work in complex fluids covers colloids, foams, granular media, rheology of non-Newtonian fluids, and emulsions and suspensions. Interfacial phenomena include liquid-vapor interface configurations, contact line dynamics, capillary-driven flows, and the shape stability and breakup of liquid bridges and drops. Dynamics and instabilities include thermocapillary and thermosolutal flows, biofluid mechanics, geological fluid flows, pattern formation, and electrokinetics and electrochemistry. Multiphase flows and phase change include flow patterns in liquid-vapor/gas flows in microgravity, nucleate boiling and its control using acoustic and electric fields in microgravity, and flows of gas-solid and liquid-solid mixtures in microgravity.

The NASA Research Announcement for microgravity fluid physics was released in December 1996. A total of 228 proposals were received in response, showing vigorous interest in microgravity fluid physics in the research community.

Some of the highlights of microgravity fluid physics research conducted in space as well as on Earth are included below.

- Startling and completely unexpected observations were made in the physics of colloids when Paul Chaikin and William Russell, of Princeton University, discovered that colloidal crystals nucleate and grow faster in microgravity than in 1 g. Indications of a possible cause come from a comparison of flight and ground dynamic data. These data suggest that

the characteristic time scales for particle motion and rearrangement may be longer in gravity than in microgravity. This is completely unexpected, and as such, it deserves further investigation. These observations resulted from the Physics of Hard Spheres Experiment conducted on the first Microgravity Science Laboratory (MSL-1) mission on the 83rd Space Transportation System flight (STS-83) and its subsequent reflight on STS-94. Precise light scattering measurements confirmed what was observed in a prior space experiment, Colloidal Disorder-Order Transition: that colloidal crystals in microgravity have a random, hexagonal, close-packed structure rather than the face-centered cubic structure predicted by theory (Zhu, et al., *Nature* 387 [26 June 1997]). The understanding of phase transitions is one of the most important problems in the field of condensed matter physics today. For this reason, physicists have long studied suspensions of simple hard spheres as models of phase transformations. These experiments on colloidal suspensions conducted in space have provided definitive conclusions that microgravity provides scientists with a unique tool to probe the secrets of nature hitherto concealed behind the veil of gravity.

- David Weitz, of the University of Pennsylvania, reported unexpected findings from his glovebox investigation, Binary Colloid Alloy Test, which was completed on the Russian space station, *Mir*, in January 1997. Photographic data were collected on 10 slowly growing samples of the binary colloid alloys over a period of 90 days, along with rapid growth data on 5 samples of colloidal gels formed from the mixtures of colloid particles and polymers. On Earth, these mixtures (colloid/polymers) form structures that collapse, presumably due to gravitational forces, after some latency time, which varies from 20 minutes to an hour. In the low-gravity environment of space on *Mir*, these structures were observed for several hours without collapse, indicating that the collapse observed on Earth is due to gravitational forces. Weitz considers this a very important finding and believes that the microgravity environment of space will allow him to study the equilibrium structures previously unachievable on Earth. Long-term growth of binary colloidal crystal alloys also showed surprising results. The sample with a volume fraction of 0.54, which did *not* crystallize on Earth, showed large crystals in space. This again indicates the influence of gravity on these processes and a clear benefit of conducting the experiment in space.
- The first-ever observation of a metastable liquid-vapor interface configuration was made in the Interface Configuration Experiment, a glovebox investigation conducted on *Mir* by astronaut Shannon Lucid. This experiment was devised to investigate the equilibrium behavior of liquid-vapor interfaces in microgravity and to verify results of mathematical models that are nearly impossible to realize in 1 g. Experiments

verified predictions of the mathematical model developed by Paul Concus, of the University of California, Berkeley, and Robert Finn, of Stanford University, in that in a symmetrical vessel, a nonsymmetric spoon-shaped interface was most stable, a saddle-shaped interface was less stable, and a symmetric concave shape was least stable. The results, which cannot be obtained on Earth, will be used to guide the use of mathematical and numerical techniques in predicting the configuration and stability of a broader range of fluid interfaces in low-gravity environments.

- In ground-based research, Harry Swinney, of the University of Texas, reported the first-ever experimental observation of long-wavelength instability in his experiments using very thin liquid layers, where the effect of gravity is negligible. A short-wavelength instability results in the formation of well-known hexagonal cells. Although this long-wavelength instability was predicted 35 years ago, it had not been observed previously. Swinney has also developed a numerical simulation that provides results which are in qualitative agreement with his experimental observations. This instability could become the primary instability in a microgravity environment.
- Jung-ho Kim, of the University of Denver, has developed an array of 96 micro heaters (0.25 mm x 0.25 mm) with the capability of running each heater in a constant temperature or constant heat flux mode through software control. This technique has the potential to answer many important questions involving boiling phenomena. For example, one relatively new hypothesis regarding critical heat flux involves looking at the surface temperatures during the boiling process. If the surface temperature is not lowered to below the Leidenfrost temperature (the temperature where a stable vapor film is formed on the surface) during the bubble departure cycle, then colder fluid from the bulk is not able to rewet the surface, and critical heat flux occurs. This can easily be tested by operating the heaters in the array in a constant power mode and using the individual heaters to map out the temperature variations on the surface during boiling.

Meetings, Awards, and Publications

Microgravity fluid physics PI Eric Kaler, of the University of Delaware Division of Colloid and Surface Chemistry, won the 1998 American Chemical Society Award in Colloid or Surface Chemistry, sponsored by Procter & Gamble. The purpose of this award is to recognize and encourage outstanding scientific contributions to colloid or surface chemistry in the United States or Canada.

Microgravity fluid physics PIs published numerous papers in prestigious journals, such as *Nature*, the *Journal of Fluid Mechanics*, *Physical Review Letters*, *Physical Review*, *Langmuir*, *Physics of Fluids*, and the *Journal of Colloids and Interface Science*.

Two microgravity fluid physics PIs, James Jenkins, of Cornell University, and Robert Behringer, of Duke University,

organized an international conference titled “Powders and Grains 97” at Duke University in May 1997. Nobel Laureate P. G. de Gennes, of the Collège de France, was the conference’s keynote speaker. He gave a talk titled “Avalanche of Granular Materials.” Several microgravity fluid physics PIs also presented papers at the conference.

Many of the fluid physics PIs served on expert panels or chaired sessions at a workshop called “Research for Space Exploration: Physical Sciences and Processes Technology,” which was held August 5–7, 1997, in Cleveland, Ohio, and was organized by Brad Carpenter and Alexander Pline, both of NASA headquarters. The purpose of the workshop was to facilitate communication between the research community, mission planners, and industry technical experts, with a goal of defining enabling research for the NASA Human Exploration and Development of Space enterprise.

The following meetings and conferences of note also took place during FY 1997:

Meeting/Conference	Date
American Physical Society’s Fluid Dynamics Meeting	October 1996
The American Institute of Chemical Engineers’ annual meeting	November 1996
The American Society of Mechanical Engineers’ Mechanical Engineering Congress and Exhibition	November 1996
The American Institute of Aeronautics and Astronautics’ Space Processing Meeting	January 1997
The Space Technology and Applications International Forum — First Conference on Application of Thermophysics in Microgravity	January 1997
The American Physical Society’s March Meeting	March 1997
The Engineering Foundation Conference on Convective Flow and Pool Boiling	May 1997
The American Society of Mechanical Engineers’ Fluids Engineering Conference	June 1997
The G. I. Taylor Symposium honoring Mathematician George Batchelor	June 1997
The American Chemical Society’s Colloids Conference	July 1997
The Microgravity Gordon Research Conference	July 1997
The National Heat Transfer Conference	August 1997

Flight Experiments

Data from the Surface Tension-Driven Convection Experiment (STDCE-2), conducted on the second United States Microgravity Laboratory (USML-2) mission, are still being analyzed. The STDCE-2 data, together with the ground-based data, show that the Marangoni number at the onset of oscillations varies with the container size, which means that the Marangoni number cannot describe the onset. Simon Ostrach and Yasuhiro Kamotani, both of Case Western Reserve University, have derived surface deformation parameters for constant temperature and constant flux configurations based on the physical model of oscillations. The model assumes that the deformability of free surface plays an important role in the oscillation mechanism. The surface deformation parameters are found to correlate with the STDCE-2 data and the ground-based data with smaller containers very well. Another important objective is to determine the velocity and temperature fields and the free surface motion during oscillations. Those quantities must have certain phase relations, according to the model of oscillations. At present, the Ronchi data are still being analyzed to determine the free surface motion. The imager data for the free surface temperature distribution have been analyzed.

Data analysis has been completed for the Pool Boiling Experiment, which successfully finished its last two reflights. The primary objective of the last two reflights, on STS-72 (January 1996) and STS-77 (May 1996), was to determine the factors governing the onset of dryout and/or rewetting on a flat heater surface. On the STS-72 mission, the subcooling levels were increased, while on the STS-77 mission, the heat flux levels were reduced. Subcooling was observed for all but the very highest heat flux levels. For lower levels of heat flux where dryout did not take place, it appeared that the excess surface energy associated with the coalescence of bubbles was sufficient to impel the resulting combined bubble away from the vicinity of the heater surface. This was sufficient to stir the liquid so as to bring the subcooled liquid to the heater surface.

Data analysis has nearly been completed for the reflight of the Thermocapillary Migration of Bubbles and Drops in Microgravity experiment, which was successfully completed on the Life and Microgravity Spacelab (LMS) mission, STS-78, utilizing the European Space Agency (ESA) facility known as the Bubble, Drop, and Particle Unit (BDPU). R. Shankar Subramanian, of Clarkson University, and Ramaswamy Balasubramaniam, of Lewis Research Center, report that in the case of isolated drops and bubbles, the LMS data appear consistent in overall trend with data from the second International Microgravity Laboratory (IML-2) while extending the range of values of the Marangoni and Reynolds numbers. Also, in axisymmetric runs in the LMS experiments, they observed, as in the case of the IML-2 experiments, that a small leading drop substantially lowered the migration speed of a larger trailing drop. However, some additional phenomena have been observed in the LMS runs that were unanticipated and interesting. In some experiments involving pairs of drops, a small leading drop moved virtually along the axis of the cell, while a larger trailing

drop moved off the axis. They also found a couple of cases of pairs of air bubbles that displayed the same asymmetric behavior in the LMS runs. Another even more interesting observation is that liquid drops in some instances moved in three-dimensional paths that were complex but appeared to be approximately helical.

Dudley Saville, of Princeton University, obtained completely unexpected results in his electrohydrodynamics experiments on the stability of liquid bridges. These experiments were also carried out on the LMS mission utilizing the BDPU. A high-voltage power supply provided voltages up to 20 kV in either AC or DC modes. Frequencies up to 500 Hz were employed. It was found that the DC field strengths required to stabilize liquid bridges in the gas were much higher than were predicted from simple scaling arguments based on the earlier ground-based two-liquid experiments and the pinned-cylinder theories developed so far. Also, the fluid bridges could not be stabilized using the AC field at strengths well over the theoretical predictions. Some new observations were a hysteresis in the field strength versus liquid bridge shapes and large, sustained oscillations under certain conditions with DC fields. Parenthetically, this experiment was a successful demonstration that one can design, fabricate, and carry out a first-class experiment in a relatively short time span. The total elapsed time from the science concept review to the flight was only a little over 18 months.

The Angular Liquid Bridge investigation, designed by Paul Concus, of the University of California, Berkeley, was conducted by astronaut Jerry Linenger in late February 1997 in the *Mir* glovebox on the *Mir-23/NASA-4* mission. The experiment was designed to explore the striking behavior of liquid-vapor interfaces in a low-gravity environment under which major shifts of liquid can arise from small changes in container configuration or contact angle. The major portion of the experiment examines configurations that liquid drops may assume between planar surfaces that may be tilted with respect to each other. Impetus for this investigation arises mainly from contrasting results obtained using classical theory. The insight gained by such work is basic for the design and analysis of fluid systems in space, such as those used for management of liquid fuel and oxygen, for thermal systems (capillary-pumped loops, heat pipes), and for biological processes (wastes and waste recycling).

The Capillary Heat Transfer investigation, designed by Kevin Hallinan, of the University of Dayton, was conducted on MSL-1 in July 1997 to investigate instabilities and failures in capillary-pumped loops (CPLs) in microgravity. CPLs require no power and can be used in satellites to transfer heat with high efficiency from electrical components to space radiators. CPLs have proven to be unreliable in space operations, and the explanation has been elusive. This experiment answered many of those questions. The glovebox investigator did observe the instabilities in the evaporator meniscus, as expected, for a capillary heat transfer device in microgravity. For heat input from the vapor side of the meniscus, the instabilities, though present, had little impact on the operation of the device. For heat input on the liquid side of the meniscus, the

instabilities produced much more violent oscillations. In some instances these oscillations caused some of the liquid in the condenser to be ejected, ultimately collecting and bridging in the bend section of the vapor return line — thereby disrupting the device operation. Evaporator dryout followed. The latter type of instabilities is not observed in 1 g due to the restoring effect of gravity. One of the more striking observations of this experiment, however, was that even if the evaporator meniscus was stable, the operation of both test devices was disrupted by the formation of a liquid slug in the vapor return line. This underscores the importance of interfacial phenomena in determining the equilibrium or low-energy liquid-vapor interface configurations in microgravity environments. These effects, if not properly accounted for, can easily lead to failure or undesirable operation of capillary-driven devices.

Physics of Colloids in Space, designed by David Weitz, of the University of Pennsylvania, and Marc Pusey, of Marshall Space Flight Center, is slated to become the first fluid physics experiment on the International Space Station, starting in January 2000. This experiment will be conducted in the EXPedite PRocessing of Experiments to Space Station (EXPRESS) rack located in the U.S. laboratory module of the station. The scientific goals of this experiment are to study fundamental colloid physics questions, colloid engineering (using colloids as precursors for the fabrication of novel materials), and properties of new materials and their precursors. Weitz and Pusey plan to conduct tests on seven samples of selected binary colloidal crystals (AB13 and AB2), emulsions, colloid/polymer mixtures, and fractal colloid gels. A requirements definition review (RDR) for this investigation was held in July 1996. Non-advocate science and engineering panels reviewed and approved the experiment's scientific merit as well as the engineering feasibility. As a result, NASA has selected this experiment for space-flight. The authority to proceed review for this experiment was held on September 26, 1997, and approval is anticipated in the near future.

The Experimental Rheology Experiment, designed by Gareth McKinley, of Harvard University, is intended to provide the first unambiguous, quantitative measurements of the transient, uniaxial, extensional viscosity for a viscoelastic polymer solution and to examine the relaxation behavior following extensional deformation. The test fluid selected for this investigation is Boger fluid composed of 0.025 wt% of high molecular weight (MW) monodisperse polystyrene (MW = 2 million) dissolved in oligomeric polystyrene. The complete test matrix involves eight non-Newtonian tests on the Boger fluid covering the Deborah number range of 0.10 to 10.0, and two Newtonian tests using the oligomeric polystyrene only. The experiments will be conducted on a Terrier Black-Brant sounding rocket with an MK70 booster that provides a microgravity duration of 300 seconds. A total of five flights are needed to complete the 10-test matrix (two tests/flight). The first flight is scheduled for the March 1999 time frame. The RDR for this investigation was held in July 1996. Nonadvocate science and engineering panels reviewed and approved the experiment's scientific merit as well as the engineering feasibility. As a result, NASA has selected this experiment for flight on a sounding rocket.

The Internal Flows in Free Drops glovebox investigation, by Satwindar Sadhal, of the University of Southern California, and Eugene Trinh, of the Jet Propulsion Laboratory, was conducted on MSL-1. The first accurate data for drop deformation as a function of acoustic pressure were obtained for a sample located at the pressure minimum plane in the ultrasonic standing wave. All ground-based data are for a drop-away from the pressure nodal plane because of gravity. The controlling parameters that affect the ability of a single-axis, ultrasonic system operating in air at ambient temperature to quiescently position a liquid drop were identified in a microgravity environment. Rotation control of a drop in microgravity was investigated. The ultimate capability of the single-axis levitator will be determined from the acquired information. Preliminary observations indicate a residual steady rotation of about 0.1 revolution per second with the acoustic power required to counteract the shuttle attitude control firings. High rotation rates necessary for drop bifurcation and fission have also been measured. Tracer particles within the deployed drops have allowed the measurement of the rotation rate, and they will yield quantitative information on the dependence of acoustic torque on pressure, as well as the assessment of the internal flow within a quasi-isothermal drop in the Spacelab environment.

The Bubble and Drop Nonlinear Dynamics glovebox investigation, by L. Gary Leal, of the University of California, Santa Barbara, and Trinh, was also conducted on MSL-1. They obtained new data not collectable in 1 g on bubble nonlinear dynamics. An effective method for bubble positioning and manipulation has been discovered, and an ultrasonic method for bubble removal has been demonstrated. The first data for nonlinear shape oscillation, free-decay frequency information for a totally free drop (no positioning force field present), were obtained, and the technique for acquiring such information was validated. Nonlinear bubble response to modulation of a combination of fundamental and harmonic ultrasonic fields has been recorded, and new behavior not previously observed has also been recorded. Large-amplitude bubble shape oscillations were excited for the first time in low gravity. The required ultrasonic field configuration for controlled bubble positioning in microgravity has been empirically determined on orbit. The method used in 1 g has been shown to fail in low gravity. Verification of the capability of an ultrasonic method for bubble removal from the liquid bulk within a closed vessel has been successfully demonstrated.

Stein Sture, of the University of Colorado, is preparing to fly the Mechanics of Granular Materials experiment on Space Shuttle *Discovery's* STS-89 mission, scheduled for January 15, 1998. The experiment was previously flown on *Atlantis* in September 1996. The Marshall Space Flight Center-sponsored experiment will test six soil specimens. Three will be subjected to the same controlled-displacement monotonic loading and unloading cycles used in the first flight; the other three will be subjected to cyclic loading. Results from the experiment's first flight showed that at low confining pressure, the soil is much stronger and stiffer than expected based on experience with similar materials on Earth. The soil specimens

will be studied using various soil mechanics measurements and video imaging while in space. After the experiment, the specimens will be impregnated with an epoxy to stabilize the sample for postmission cross-cut sectioning and various internal imaging techniques. Specimens from the previous mission were studied using X-ray computer tomography scans performed at the Los Alamos National Labs in New Mexico. This was the first time the nondestructive imaging technique was successfully used on a soil particle experiment. Data about the soil deformation were also

obtained from video images taken on orbit and from laser profilometer testing, which was used to ascertain precisely how the surface of each specimen was deformed during the experiment.

The fiscal year (FY) 1997 ground and flight tasks for fluid physics are listed in **Table 5**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Table 5 Fluid physics tasks funded by the Microgravity Research Division in FY 1997
(includes some continuing projects at no additional cost)

Flight Experiments

Two-Phase Gas-Liquid Flows in Microgravity: Experimental and Theoretical Investigation of the Annular Flow

Vemuri Balakotaiah
University of Houston, Houston, TX

The Dynamics of Disorder-Order Transitions in Hard Sphere Colloidal Dispersions

Paul M. Chaikin
Princeton University, Princeton, NJ

Investigations of Mechanisms Associated With Nucleate Boiling Under Microgravity Conditions

Vijay K. Dhir
University of California, Los Angeles, Los Angeles, CA

Microscale Hydrodynamics Near Moving Contact Lines

Stephen Garoff
Carnegie Mellon University, Pittsburgh, PA

Geophysical Fluid Flow Cell

John E. Hart
University of Colorado, Boulder, Boulder, CO

Growth and Morphology, Boiling, and Critical Fluctuations of Phase-Separating Supercritical Fluids

John Hegseth
University of New Orleans, New Orleans, LA

An Experimental Study of Richtmyer-Meshkov Instability in Low Gravity

Jeffrey W. Jacobs
University of Arizona, Tucson, AZ

Microgravity Segregation in Binary Mixtures of Inelastic Spheres Driven by Velocity Fluctuation Gradients

James T. Jenkins
Cornell University, Ithaca, NY

Bubble Dynamics on a Heated Surface

Mohammad Kassemi
Ohio Aerospace Institute, Cleveland, OH

Magnetorheological Fluids: Rheology and Nonequilibrium Pattern Formation

Jing Liu
California State University, Long Beach, Long Beach, CA

Extensional Rheology Experiment

Gareth H. McKinley
Harvard University, Cambridge, MA

Study of Two-Phase Gas-Liquid Flow Behavior at Reduced-Gravity Conditions

John McQuillen
Lewis Research Center, Cleveland, OH

Pool Boiling Experiment

Herman Merte, Jr.
University of Michigan, Ann Arbor, MI

Surface Tension-Driven Convection Experiment (STDCE-1, STDCE-2)

Simon Ostrach
Case Western Reserve University, Cleveland, OH

Behavior of Rapidly Sheared, Bubbly Suspensions

Ashok S. Sangani
Syracuse University, Syracuse, NY

Studies in Electrohydrodynamics

Dudley A. Saville
Princeton University, Princeton, NJ

Mechanics of Granular Materials

Stein Sture
University of Colorado, Boulder, Boulder, CO

Thermocapillary Migration and Interactions of Bubbles and Drops

R. Shankar Subramanian
Clarkson University, Potsdam, NY

A Study of the Constrained Vapor Bubble Heat Exchanger

Peter C. Wayner, Jr.
Rensselaer Polytechnic Institute, Troy, NY

Physics of Colloids in Space

David A. Weitz
University of Pennsylvania, Philadelphia, PA

Ground-Based Experiments

Experimental and Analytical Study of Two-Phase Flow Parameters in Microgravity

Davood Abdollahian
S. Levy Incorporated, Campbell, CA

Colloids and Nucleation

Bruce J. Ackerson
Oklahoma State University, Stillwater, OK

Dynamics and Statics of Nonaxisymmetric Liquid Bridges

J. Iwan D. Alexander
University of Alabama, Huntsville, Huntsville, AL

Numerical Simulation of Electrochemical Transport Processes in Microgravity Environments

Sanjoy Banerjee
University of California, Santa Barbara, Santa Barbara, CA

Control of Flowing Liquid Films by Electrostatic Fields in Space

S. George Bankoff
Northwestern University, Evanston, IL

Forced Oscillation of Pendant and Sessile Drops

Osman A. Basaran
Purdue University, West Lafayette, IN

Dynamics of Granular Materials

Robert P. Behringer
Duke University, Durham, NC

Investigation of Drop Formation by a Vortex Ring in Microgravity

Luis P. Bernal
University of Michigan, Ann Arbor, MI

Dynamic Modeling of the Microgravity Flow

Jeremiah U. Brackbill
Los Alamos National Laboratory, Los Alamos, NM

Marangoni Instability-Induced Convection in Evaporating Liquid Droplets

An-Ti Chai
Lewis Research Center, Cleveland, OH

Rewetting of Monogroove Heat Pipe in Space Station Radiators

S. H. Chan
University of Wisconsin, Milwaukee, Milwaukee, WI

Bubble Dynamics, Two-Phase Flow, and Boiling Heat Transfer in Microgravity

Jacob N. Chung
Washington State University, Pullman, WA

Structure, Hydrodynamics, and Phase Transitions of Freely Suspended Liquid Crystals

Noel A. Clark
University of Colorado, Boulder, Boulder, CO

Fluid Interface Behavior Under Low- and Zero-Gravity Conditions

Paul Concus
University of California, Berkeley, Berkeley, CA

Interface Morphology During Crystal Growth: Effects of Anisotropy and Fluid Flow

Sam R. Coriell
National Institute of Standards and Technology, Gaithersburg, MD

Phoretic and Radiometric Force Measurements on Microparticles Under Microgravity Conditions

E. James Davis
University of Washington, Seattle, WA

Cell and Particle Interactions and Aggregation During Electrophoretic Motion

Robert H. Davis
University of Colorado, Boulder, Boulder, CO

Interaction and Aggregation of Colloidal Biological Particles and Droplets in Electrically Driven Flows

Robert H. Davis
University of Colorado, Boulder, Boulder, CO

Theory of Solidification

Stephen H. Davis
Northwestern University, Evanston, IL

The Melting of Aqueous Foams

Douglas J. Durian
University of California, Los Angeles, Los Angeles, CA

Magneto-thermal Convection in Nonconducting Diamagnetic and Paramagnetic Fluids

Boyd F. Edwards
West Virginia University, Morgantown, WV

Effects of Gravity on Sheared Turbulence Laden With Bubbles or Droplets

Said E. Elghobashi
University of California, Irvine, Irvine, CA

Evaporation, Boiling, and Condensation on/in Capillary Structures of High Heat Flux Two-Phase Devices

Amir Faghri
University of Connecticut, Storrs, CT

The Influence of Gravity on Colloidal Crystallization and Field-Induced Aggregation

Alice P. Gast
Stanford University, Stanford, CA

Material Instabilities in Particulate Systems

Joe D. Goddard
University of California, San Diego, La Jolla, CA

Thermoacoustic Effects at a Solid-Fluid Boundary: The Role of a Second-Order Thermal Expansion Coefficient

Ashok Gopinath
Naval Postgraduate School, Monterey, CA

Instability Mechanisms in Thermally Driven Interfacial Flows in Liquid-Encapsulated Crystal Growth

Hossein Haj-Hariri
University of Virginia, Charlottesville, VA

A Study of the Microscale Fluid Physics in the Near-Contact Line Region of an Evaporating Capillary Meniscus

Kevin P. Hallinan
University of Dayton, Dayton, OH

Interfacial Transport and Micellar Solubilization Processes

T. Alan Hatton
Massachusetts Institute of Technology, Cambridge, MA

A Geophysical Flow Experiment in a Compressible Critical Fluid

John Hegseth
University of New Orleans, New Orleans, LA

Experimental Investigation of Pool Boiling Heat Transfer Enhancement in Microgravity in the Presence of Electric Fields

Cila Herman
Johns Hopkins University, Baltimore, MD

Problems in Microgravity Fluid Mechanics: Thermocapillary Instabilities and G-Jitter Convection

George M. Homsy
Stanford University, Stanford, CA

Surfactant-Based Critical Phenomena in Microgravity

Eric W. Kaler
University of Delaware, Newark, DE

Bubble Generation in a Flowing Liquid Medium and Resulting Two-Phase Flow in Microgravity

Yasuhiro Kamotani
Case Western Reserve University, Cleveland, OH

Instability of Velocity and Temperature Fields in the Vicinity of a Bubble on a Heated Surface

Mohammad Kassemi
Ohio Aerospace Institute, Cleveland, OH

Studies in Thermocapillary Convection of the Marangoni-Bénard Type

Robert E. Kelly
University of California, Los Angeles, Los Angeles, CA

Two-Phase Annular Flow in Helical Coil Flow Channels in a Reduced-Gravity Environment

Edward G. Keshock
Cleveland State University, Cleveland, OH

Investigation of Pool Boiling Heat Transfer Mechanisms in Microgravity Using an Array of Surface-Mounted Heat Flux Sensors

Jungho Kim
University of Denver, Denver, CO

Molecular Dynamics of Fluid-Solid Systems

Joel Koplik
City College of the City University of New York, New York, NY

Thermocapillary Convection in Low Pr Materials Under Simulated Reduced-Gravity Conditions

Sindo Kou
University of Wisconsin, Madison, WI

Electric Field-Induced Interfacial Instabilities

Robert E. Kusner
Lewis Research Center, Cleveland, OH

The Breakup and Coalescence of Gas Bubbles Driven by the Velocity Gradients of a Nonuniform Flow

L. Gary Leal
University of California, Santa Barbara, Santa Barbara, CA

Oscillatory Cross-Flow Electrophoresis: Application to Production-Scale Separations

David T. Leighton
University of Notre Dame, Notre Dame, IN

The Micromechanics of the Moving Contact Line

Seth Lichter
Northwestern University, Evanston, IL

Absolute and Convective Instability and Splitting of a Liquid Jet at Microgravity

Sung P. Lin
Clarkson University, Potsdam, NY

Magnetorheological Fluids in Microgravity

Jing Liu
California State University, Long Beach, Long Beach, CA

Rheology of Concentrated Emulsions

Michael Loewenberg
Yale University, New Haven, CT

Investigation of Thermal Stress Convection in Nonisothermal Gases Under Microgravity Conditions

Daniel W. Mackowski
Auburn University, Auburn, AL

The Dissolution of an Interface Between Miscible Liquids

James V. Maher
University of Pittsburgh, Pittsburgh, PA

Passive or Active Radiation Stress Stabilization of (and Coupling to) Liquid Bridges and Bridge Networks

Philip L. Marston
Washington State University, Pullman, WA

Fundamental Processes of Atomization in Fluid-Fluid Flows

Mark J. McCready
University of Notre Dame, Notre Dame, IN

Fluid Dynamics and Solidification of Molten Solder Droplets Impacting on a Substrate in Microgravity

Constantine M. Megaridis
University of Illinois, Chicago, Chicago, IL

A Study of Nucleate Boiling With Forced Convection in Microgravity

Herman Merte, Jr.
University of Michigan, Ann Arbor, MI

Determination of Interfacial Rheological Properties Through Microgravity Oscillations of Bubbles and Drops

Ali Nadim
Boston University, Boston, MA

NMRI Measurements and Granular Dynamics Simulations of Segregation of Granular Mixtures

Masami Nakagawa
Colorado School of Mines, Golden, CO

Control of Oscillatory Thermocapillary Convection in Microgravity

G. Paul Neitzel
Georgia Institute of Technology, Atlanta, GA

Noncoalescence Effects in Microgravity

G. Paul Neitzel
Georgia Institute of Technology, Atlanta, GA

Production of Gas Bubbles in Reduced-Gravity Environments

Hasan N. Oguz
Johns Hopkins University, Baltimore, MD

Waves in Radial Gravity Using Magnetic Fluid

Daniel R. Ohlsen
University of Colorado, Boulder, Boulder, CO

Industrial Processes Influenced by Gravity

Simon Ostrach
Case Western Reserve University, Cleveland, OH

On the Boundary Conditions at an Oscillating Contact Line: A Physical/Numerical Experimental Program

Marc Perlin
University of Michigan, Ann Arbor, MI

Acoustic Bubble Removal From Boiling Surfaces

Andrea Prosperetti
Johns Hopkins University, Baltimore, MD

Containerless Ripple Turbulence

Seth J. Putterman
University of California, Los Angeles, Los Angeles, CA

Decoupling the Role of Inertia and Gravity on Particle Dispersion

Chris B. Rogers
Tufts University, Medford, MA

Design/Interpretation of Microgravity Experiments to Obtain Fluid/Solid Boundary Conditions in Nonisothermal Systems

Daniel E. Rosner
Yale University, New Haven, CT

Gas Flow From Porous Media and Microgravity Battery Spills

Robert T. Ruggeri
The Boeing Company, Seattle, WA

Ground-Based Studies of Internal Flows in Levitated Laser-Heated Drops

Satwindar S. Sadhal
University of Southern California, Los Angeles, CA

Dielectric and Electrohydrodynamic Properties of Suspensions

Dudley A. Saville
Princeton University, Princeton, NJ

Terrestrial Experiments on G-Jitter Effects on Transport and Pattern Formation

Michael F. Schatz
Georgia Institute of Technology, Atlanta, GA

Free-Surface and Contact-Line Motion of Liquids in a Microgravity Environment

Leonard W. Schwartz
University of Delaware, Newark, DE

Drop Breakup in Flow Through Fixed Beds as Model Stochastic Strong Flows

Eric S. G. Shaqfeh
Stanford University, Stanford, CA

Electrohydrodynamic Pool Boiling in Reduced Gravity

Benjamin D. Shaw
University of California, Davis, Davis, CA

Transport Processes Research

Bhim S. Singh
Lewis Research Center, Cleveland, OH

Solute Nucleation and Growth in Supercritical Fluid Mixtures

Gregory T. Smedley
California Institute of Technology, Pasadena, CA

Behavior of Unsteady Thermocapillary Flows

Marc K. Smith
Georgia Institute of Technology, Atlanta, GA

The Development of Novel, High-Flux, Heat Transfer Cells for Thermal Control in Microgravity

Marc K. Smith
Georgia Institute of Technology, Atlanta, GA

Dynamics of the Molten Contact Line

Ain A. Sonin
Massachusetts Institute of Technology, Cambridge, MA

Marangoni Effects on Drop Deformation and Breakup in an Extensional Flow: The Role of Surfactant Physical Chemistry

Kathleen J. Stebe
Johns Hopkins University, Baltimore, MD

Stability of Shapes Held by Surface Tension and Subjected to Flow

Paul H. Steen
Cornell University, Ithaca, NY

Instabilities in Surface Tension-Driven Convection

Harry L. Swinney
University of Texas, Austin, Austin, TX

Crystal Growth and Fluid Mechanics Problems in Directional Solidification

Saleh Tanveer
Ohio State University, Columbus, OH

Microgravity Effects on Transendothelial Transport

John M. Tarbell
Pennsylvania State University, University Park, PA

Light-Scattering Studies of Relative Motions of Solid Particles in Turbulent Flows

Penger Tong
Oklahoma State University, Stillwater, OK

Studies of Particle Sedimentation by Novel Scattering Techniques

Penger Tong
Oklahoma State University, Stillwater, OK

Acoustic Streaming in Microgravity: Flow Stability and Heat Transfer Enhancement

Eugene H. Trinh
Jet Propulsion Laboratory, Pasadena, CA

Fluid Physics in a Stochastic Acceleration Environment

Jorge Viñals
Florida State University, Tallahassee, FL

Residual Accelerations in a Microgravity Environment

Jorge Viñals
Florida State University, Tallahassee, FL

Fundamental Physics Overview

The goal of the fundamental physics program is to use the microgravity environment of space to shed light on the most fundamental physical laws that govern the behavior of matter. An understanding of these laws, and the advanced technology developed in order to study them with unprecedented precision, are useful in applications that support and enhance human presence in space, improve the quality of life on Earth, and contribute to the competitiveness of American industry. The microgravity fundamental physics research program currently includes research in the areas of low-temperature and condensed matter physics (LTCMP), laser cooling and atomic physics (LCAP), and gravitational and relativistic physics (GRP). One of the strengths of the fundamental physics discipline is the significant synergy that exists across the three subdisciplines in terms of both scientific convergence and overlap in experimental techniques. Both experimental and theoretical research is being funded.

In fiscal year (FY) 1997, the focus in the LTCMP area was on high-resolution tests of the renormalization group (RG) theory, studies of finite size effects in matter, studies of quantum solidification, and studies of levitated helium drops. The RG theory constitutes one of the greatest achievements of theoretical physics in the past 30 years. The increased understanding of the validity of use of the RG theory in such disciplines as percolation, pattern formation, and evolution of turbulence will help scientists develop better models for how water seeps through soil, how frost heaving occurs in arctic climates, and how turbulent weather systems evolve, among other things.

In the LCAP area, the research focus over the last year has been on development of advanced clocks; studies of fundamental forces and symmetries of nature, such as measurements of the electric dipole moment of the electron; and studies of Bose-Einstein condensation (BEC). An advanced technology development proposal to develop the core flight technology required for LCAP investigators currently in the program was successfully defended. The development of this technology will serve as the first step in providing LCAP investigators access to space.

In the GRP area, the research focus in the last year has been on development of advanced hardware to perform high-resolution tests of Einstein's equivalence principle. The Satellite Test of the Equivalence Principle (STEP) experiment has the objective of testing an underlying postulate of the theory of general relativity — the principle of the equivalence of inertial mass and gravitational mass — to a precision of about one part in 10^{18} . Efforts last year focused on developing and demonstrating several critical technologies required for the STEP instrument, particularly in regard to superconducting accelerometers. Agreements for cooperation are being negotiated with representatives of the European Space Agency (ESA) and with national space agencies in Europe. To firmly validate the scientific importance of STEP, it was repropounded as part of the 1996 Fundamental Physics NASA Research Announcement (NRA). The results of the evaluation are expected to become available early next year.

The requirements definition review (RDR) for Critical Dynamics in Microgravity (DYNAMX) was conducted in February 1997. The science and programmatic/engineering review panels recommended additional work be completed prior to proceeding to flight. Both panels recommended a delta RDR in about a year. NASA headquarters and the Microgravity Research Program Office at Marshall Space Flight Center endorsed this recommendation. The DYNAMX project team reacted to the RDR recommendations by reorganizing activities under direct science leadership strengthened by the addition of John Lipa, of Stanford University, as a technical consultant and David Goodstein, of the California Institute of Technology, as an overall science consultant. Sensors have been redesigned and refabricated, and the process of incorporating this new hardware into the ground test facility in order to conduct the final testing required to demonstrate experiment feasibility is under way. In August, the project was directed to replan for flight on the International Space Station (ISS) Low-Temperature Microgravity Physics Facility (LTMPF) in 2003. Specific scientific accomplishments by DYNAMX reported in the open literature include the first experimental observation of self-organized criticality in ^4He and preliminary results indicating the existence of nonlinear thermal transport previously predicted by theory. Robert Duncan, of the University of New Mexico, is the principal investigator (PI) for DYNAMX.

The Microgravity Scaling Theory Experiment (MISTE) is a flight definition experiment planned for operation on the ISS. Martin Barmatz, of the Jet Propulsion Laboratory (JPL), is the PI for this experiment. MISTE will measure three critical exponents near the gas-liquid critical point in ^3He in the same apparatus, thus allowing rigorous tests of theories for the scaling and hyperscaling relationships between these exponents. Performing the measurements in microgravity will permit these critical parameters to be measured very close to the phase transition where asymptotic critical point behavior is clearly dominant. During FY 1997, Barmatz participated in the planning of the ISS LTMPF by serving on the science planning committee. Precision ground-based measurements are now being performed in preparation for MISTE's science concept review (SCR), scheduled for November 1998.

The Superfluid Universality Experiment (SUE) was chosen in February 1996 to be a flight definition experiment for operation on the ISS. SUE will measure properties of superfluid helium just below the phase transition to determine critical parameters at the transition. These measurements will be repeated at several pressures to test theories of the universality predictions of such transitions. Of critical importance to the success of SUE is the development of high-resolution pressure control capability. Activities in 1997 focused largely on demonstrating and validating this new technology. Last year's effort also included participation on the science planning team for the ISS LTMPF. The SCR for SUE is scheduled for November 1998. Lipa is the PI for SUE.

Of note in the fundamental physics discipline is the fact that researchers generally must advance the state of the art in technology

in order to take full advantage of the opportunities offered by the space environment. These advancements in technology can be applied to other endeavors in support of American commerce or in support of the presence of humans in space. Example technologies include superconducting magnetometers for efficient resource mining and noninvasive medical diagnostics; management of cryogenic fluids for life support systems and manufacturing use; and use of highly accurate, low-temperature clocks for navigation, global positioning, and communications.

The second fundamental physics NRA was released in FY 1997, and 86 proposals were received in response. Many of the proposals were for new, innovative research directions in all three subdisciplines. To review the proposals, NASA assembled high-quality panels, including a “blue ribbon” panel with two Nobel laureates. Selection of research for funding is expected in early FY 1998. In addition, two glovebox research proposals were developed and submitted for review last year.

The Fundamental Physics Steering Group, with advice and assistance from other scientists in the ground-based and flight programs, finalized a science plan for the discipline. This plan will be updated on an annual basis to represent a discipline science outlook with about a 5- to 10-year horizon.

A few notable achievements during FY 1997 ground-based investigations are listed below.

- George Seidel, of Brown University, successfully suspended drops of liquid helium using a nonuniform magnetic field. He was able to observe motions of the drops and could control their spin with electric forces after applying charges to the drops. Unusual noncoalescence behavior was observed for two drops in the potential well, which was explained as being due to vapor occurring between the drops to isolate them from each other.
- Horst Meyer, of Duke University, and Guenter Ahlers, of the University of California, Santa Barbara (UCSB), resolved an old discrepancy in the data for the heat flow resistance at the interface between a solid surface and liquid helium. New data at Duke and at UCSB for the boundary-resistance anomaly as the lambda point transition is approached now agree, resolving a difference in earlier results. Rebuilding the experimental cell to eliminate very small gaps was crucial to these measurements.
- Kurt Gibble, of Yale University, has demonstrated the feasibility of critical technologies needed for development of a rubidium-based microgravity clock.
- Dan Heinzen, of the University of Texas, Austin, observed Bose-Einstein condensation in rubidium.
- Robert Chave, of JPL, developed a magnetostrictive valve operating at low temperature with a very small fluid volume. The valve was cycled over 100 times at low temperature.

Valve demonstration with a high-temperature, superconducting solenoid was also performed.

- Results from ground-based investigations have been published in 31 presentations, 19 proceeding papers, and 36 articles in refereed journals.
- Fundamental physics investigations have supported 29 students who are working toward their doctoral degrees and 10 undergraduate students. Five graduate students received their doctoral degrees in FY 1997.

Meetings, Awards, and Publications

This year’s Nobel Prize in physics was awarded to three scientists responsible for the development of laser cooling and trapping of atoms. Steve Chu, of Stanford University; William D. Phillips, of the National Institute of Science and Technology; and Claude Cohen-Tannoudji, of École Normale Supérieure in France, were recognized for their contribution to the field of laser cooling and trapping. These accomplishments have already led to important developments such as the observation of Bose-Einstein condensation in a dilute gas of atoms and the potential for ultraprecise atomic clocks for ground and space applications. Chu and Phillips have been involved in various capacities in the NASA fundamental physics program during the last few years.

The 1997 Fundamental Physics Investigators Workshop drew 62 attendees to Santa Barbara, California, May 7–9. Several of the investigators reported new findings that raised questions concerning discrepancies with existing theories. One of the more exciting announcements was Heinzen’s report of his group’s verging upon observing Bose-Einstein condensed atoms (Heinzen announced the observation of BEC shortly after the workshop). Rob Duncan, of the University of New Mexico, who is the PI for DYNAMX, presented beautiful new data showing helium in a self-organized state near the lambda transition. Prospects for performing meaningful tests of theories of relativity and gravitation in the STEP investigation were described by Francis Everitt and Saps Buchman, both of Stanford University. Special sessions describing plans for the development of facilities for the ISS brought out the need for investigator input to establish requirements envelopes for these facilities. Mike Devirian, of JPL, described the recent and planned growth in this program and pointed to new opportunities for glovebox experiments and for near-term shuttle flights; two new glovebox experiments were proposed as a result of discussions at the workshop. Mark C. Lee, of NASA headquarters, illustrated the evolution of a program for support by the fundamental physics program of the Human Exploration and Development of Space enterprise, inviting the investigators to contribute to the ideas being advanced. Ahlers presented the science plan for fundamental physics, asking for comments from the investigators to help

refine the concepts described in the document. Proceedings, consisting of summaries of the presentations, will be published as a NASA document.

Several members of the fundamental physics discipline attended the Symposium on Physical Sciences in Microgravity in St. Petersburg, Russia, June 15–21, 1997. This symposium covered a broad area of microgravity science and applications, including combustion science, fluid physics, fundamental physics, and materials science, and was attended by 200–300 scientists and engineers. The symposium provided a valuable opportunity to mingle with people from other microgravity disciplines. Ahlers gave an invited plenary talk (one of only three for the entire meeting). This talk was an opportunity to explain to the broader community the exciting developments in microgravity fundamental physics that are taking place right now. The presentation was received with much interest by our colleagues in the broad microgravity science community.

A workshop on low-temperature microgravity physics was held in Chernogolovka, Russia, June 23–27, 1997. The workshop was organized by the Institute of Solid State Physics of the Russian Academy of Science and was chaired by the institute's director, Yuri Ossipyan. About 50 scientists were in attendance to hear 23 scientific papers presented in the areas of low-temperature and condensed matter physics, laser cooling and atomic physics, and gravitational physics by participants from Japan, Russia, the Ukraine, and the United States. Many papers represented scientific results obtained by international teams of researchers. Six investigators in the fundamental physics program represented NASA. The proceedings of this workshop will be published in the Russian language journal *Fizika Nizkikh Temperatur (Low-Temperature Physics)*.

The Quantum Fluids Workshop, organized by École Normale Supérieure, was held in Paris, France, July 21–25. About 250 international participants, including three Nobel Prize winners, were in attendance. The scientific program included 192 presentations in condensed matter physics and in laser cooling and atomic physics. Six U.S. microgravity fundamental physics investigators attended the meeting, along with 18 additional presenters with strong ties to this microgravity program. The DYNAMX flight project presented preliminary results showing the first measurements of nonlinear thermal conductivity data. Following peer review, the meeting contributions will be published in the *Journal of Low Temperature Physics*.

The Space Cryogenics Workshop, jointly organized by JPL and the University of Oregon Physics Department, was held in Eugene, Oregon, August 4–5. NASA's Microgravity Research Division and its Office of Space Science jointly sponsored the workshop. At the workshop, the latest developments in space cryogenics were discussed. Following peer review, the workshop contributions will be published in the journal *Cryogenics*.

Flight Experiments

The Confined Helium Experiment (CHeX), which studies fundamental questions regarding the influence of boundaries on the behavior of matter, completed system integration and testing at JPL about midway through the year and was shipped to Kennedy Space Center (KSC) for launch integration. At KSC, CHeX completed integration verification testing with the Mission Peculiar Experiment Support Structure carrier and was ready for transport to the pad. CHeX was launched on the space shuttle as part of the fourth United States Microgravity Payload (USMP-4) mission on November 19, 1997. Lipa is the PI for CHeX.

The Critical Fluid Light-Scattering Experiment (Zeno) successfully completed its second flight on the USMP-3 mission last year. FY 1997 was spent on completing the data analysis and in preparing manuscripts for publication. This experiment extends and improves measurements of the decay rates and the correlation length of critical fluctuations in a simple fluid very near its liquid-vapor critical point. While the experiment fell short of its full potential due to problems with the density of the xenon vapor sample, the measurements achieved were substantially closer to the critical temperature than can be attained on Earth. The PI for Zeno is Robert Gammon, of the University of Maryland.

The Critical Viscosity Experiment (CVX) successfully flew on the first True Air Speed (TAS-01) payload as part of the 85th Space Transportation System (STS-85) mission in August. The mission was extended by one day to allow the CVX team to collect additional data. The experiment performed exceptionally well and collected data for nearly the entire 11-day mission. The main objective of the CVX experiment was to measure the viscosity of xenon to within 0.3 percent of the critical density and to within 0.6 mK of the critical temperature (T_c), which is 30 times closer than can be measured on Earth. Preliminary analysis of the data suggests that accurate viscosity measurements were obtained to within about 1 mK of T_c and possibly as close as 0.6 mK. The weak divergence of the viscosity was clearly seen in the microgravity environment and was approximately twice as large as the best measurements on Earth. The divergence is strongly masked in Earth's gravity due to stratification of the fluid density. Data analysis and manuscript preparations will be continued throughout next year. The PI for CVX is Robert Berg, of the National Institute for Standards and Technology.

The FY 1997 ground and flight tasks for fundamental physics are listed in **Table 6**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Table 6 **Fundamental physics tasks funded by the Microgravity Research Division in FY 1997**
(includes some continuing projects at no additional cost)

Flight Experiments

Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^3He

Martin B. Barmatz
 Jet Propulsion Laboratory, Pasadena, CA

Critical Viscosity of Xenon

Robert F. Berg
 National Institute of Standards and Technology, Gaithersburg, MD

Critical Dynamics in Microgravity

Robert V. Duncan
 University of New Mexico, Albuquerque, NM

Satellite Test of the Equivalence Principle

C. W. Francis Everitt
 Stanford University, Stanford, CA

Critical Fluid Light-Scattering Experiment

Robert W. Gammon
 University of Maryland, College Park, College Park, MD

Confined Helium Experiment

John A. Lipa
 Stanford University, Stanford, CA

A New Test of Critical-Point Universality by Measuring the Superfluid Density Near the Lambda Line of Helium

John A. Lipa
 Stanford University, Stanford, CA

Ground-Based Experiments

The Superfluid Transition of ^4He Under Unusual Conditions

Guenter Ahlers
 University of California, Santa Barbara, Santa Barbara, CA

New Phenomena in Strongly Counterflowing He-II Near T_λ

Stephen T. Boyd
 University of New Mexico, Albuquerque, NM

Prediction of Macroscopic Properties of Liquid Helium From Computer Simulation

David M. Ceperley
 University of Illinois, Urbana-Champaign, Urbana, IL

The Lambda Transition Under Superfluid Flow Conditions

Talso C. P. Chui
 Jet Propulsion Laboratory, Pasadena, CA

Nucleation of Quantized Vortices From Rotating Superfluid Drops

Russell J. Donnelly
 University of Oregon, Eugene, OR

Kinetic and Thermodynamic Studies of Melting-Freezing of Helium in Microgravity

Charles Elbaum
 Brown University, Providence, RI

Critical Dynamics of Ambient Temperature and Low-Temperature Phase Transitions

Richard A. Ferrell
 University of Maryland, College Park, College Park, MD

Investigation of Future Microgravity Atomic Clocks

Kurt Gibble
 Yale University, New Haven, CT

Precision Measurements with Trapped, Laser-Cooled Atoms in a Microgravity Environment

Daniel J. Heinzen
 University of Texas, Austin, Austin, TX

Collisional Frequency Shifts Near Zero-Energy Resonance

Randall G. Hulet
 Rice University, Houston, TX

Dynamic Measurements Along the Lambda Line of Helium in a Low-Gravity Simulator on the Ground

Ulf E. Israelsson
 Jet Propulsion Laboratory, Pasadena, CA

Second Sound Measurements Near the Tricritical Point in ^3He - ^4He Mixtures

Melora E. Larson
 Jet Propulsion Laboratory, Pasadena, CA

Static Properties of ^4He in the Presence of a Heat Current in a Low-Gravity Simulator

Melora E. Larson
 Jet Propulsion Laboratory, Pasadena, CA

Red-Shift Test of General Relativity on Space Station Using Superconducting Cavity Oscillators

John A. Lipa
 Stanford University, Stanford, CA

A Renewal Proposal to Study the Effect of Confinement on Transport Properties by Making Use of Helium Along the Lambda Line

John A. Lipa
 Stanford University, Stanford, CA

Theoretical Studies of Liquid ^4He Near the Superfluid Transition

Efstratios Manousakis
 Florida State University, Tallahassee, FL

Density Equilibration in Fluids Near the Liquid-Vapor Critical Point

Horst Meyer
 Duke University, Durham, NC

Indium Mono-Ion Oscillator II

Warren Nagourney
 University of Washington, Seattle, WA

Nonlinear Relaxation and Fluctuations in a Nonequilibrium, Near-Critical Liquid With a Temperature Gradient

Alexander Z. Patashinski
 Northwestern University, Evanston, IL

Superfluid Density of Confined ^4He Near T_λ

David Pearson
 Jet Propulsion Laboratory, Pasadena, CA

Finite Size Effects Near the Liquid-Gas Critical Point of ^3He

Joseph Rudnick
 University of California, Los Angeles, Los Angeles, CA

Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment

George M. Seidel
 Brown University, Providence, RI

Precise Measurements of the Density and Critical Phenomena of Helium Near Phase Transitions

Donald M. Strayer
 Jet Propulsion Laboratory, Pasadena, CA

Materials Science Overview

The goal of the materials science research program is to establish and improve the quantitative and predictive relationships in the structure, processing, and properties of materials. Production processes for most materials include steps that are very heavily influenced by the force of gravity. Typical gravity-related effects on materials science research include buoyancy-driven convection, sedimentation, and hydrostatic pressure. The opportunity to observe, monitor, and study material production in low gravity promises to increase our fundamental understanding of production processes and their effects on the properties of the materials produced. By careful modeling and experimentation, the mechanisms by which materials are formed can be better understood and can result in improved processing controls. In this way, materials scientists can design new metal alloys, semiconductors, ceramics, glasses, and polymers to improve the performance of a wide range of products, such as complex computers and stronger, more durable metal alloys.

Several important events took place during fiscal year (FY) 1997, such as the successful flights of the Liquid Metal Diffusion (LMD) investigation in January, the first Microgravity Science Laboratory (MSL-1) mission in April, and the reflight of the MSL mission (MSL-1R) in July. The materials science program placed an emphasis on ensuring that principal investigators (PIs) conducting flight-based experiments successfully completed the flight definition phase major reviews, including the science concept review (SCR) and the requirements definition review (RDR), in a timely manner through dedicated NASA and PI teams. Also during FY 1997, the materials science program began implementation of NASA's Human Exploration and Development of Space (HEDS) enterprise Strategic Plan, which includes goals, performance measurements, and metrics. The HEDS Strategic Plan, which has direct benefits for the nation, provides the framework for conducting materials science research.

In the spring, the Committee on Materials Science Research on the International Space Station (ISS) was convened under the auspices of the National Research Council to examine NASA's research plan for microgravity materials science with respect to evolving interests and priorities in the field of materials science. Additionally, the committee assessed the Space Station Furnace Facility (SSFF) concept with respect to its specific research capabilities, technology, and usefulness to the U.S. materials science community. The committee's review reconfirmed the value of research conducted in NASA's materials science program, but recommended that NASA expand the range of experiments and classes of materials (such as glasses, ceramics, and polymers) that the SSFF could accommodate. NASA addressed the council's concerns by beginning work toward the design of a more flexible flight facility that would accommodate a wider variety of materials investigations and be more compatible with available power, volume, upmass, and crew resources on the ISS. The new concept is known as the Materials Science Research Facility (MSRF). The MSRF consists of independent, modular racks, each of which will

be comprised of experiment modules that can be replaced on orbit; module inserts; and investigation-unique apparatus and/or multiuser, generic processing apparatus that will support a wide variety of scientific investigations. The first rack is targeted for the third Utilization Flight (UF-3) to the ISS.

In December 1996, the NASA Research Announcement for materials science was issued. Over 200 proposals were received and reviewed by selection panels. It is anticipated that the selection of flight and ground PIs will be announced in the first quarter of FY 1998. For the flight definition investigations selected from the 1994 research announcement, SCRs are planned for FY 1998, and RDRs are planned for FY 1999.

Meetings, Awards, and Publications

The Scientific and Technological Advisory Council (STAC) met in Huntsville, Alabama, November 10-13, 1997. STAC is the Russian organization responsible for program management and implementation of U.S.-funded Russian space research. The purpose of the conference was to present experiment results. The conference was attended by approximately 60 high-ranking Russian scientists and administrators, many of whom are members of the Russian Academy of Sciences, as well as participants from the Alliance for Microgravity Materials Science and Applications (AMMSA). Among those AMMSA members who gave presentations at the conference were Marc Pusey (co-chair and presenter for the Space Biotechnology session); William Witherow and Alexander Chernov (presenters for the Space Biotechnology session); Iwan Alexander (co-chair and presenter for the Space Technology and Materials Science session); and Donald Gillies, Sandor Lehoczky, Ching-Hua Su, and Frank Szofran (presenters for the Space Technology and Materials Science session). Among those AMMSA members who provided general support were Danna McCauley, who coordinated the AMMSA support; Charlie Walker and Leonard Williams, who provided computer support; and Jean George, Nancy Marsh, and Sue Zarger, who provided daily support at the conference's help tables. A tour of Marshall Space Flight Center (MSFC) was conducted and included stops at the Global Hydrology and Climate Control building, the Space Sciences Laboratory, the Microgravity Development Laboratory, the drop tower, the space station mockups, and the Structural Biotechnology Laboratory. A separate tour was provided of selected facilities at the University of Alabama in Huntsville.

The Society of Photo-Optical Instrumentation Engineers (SPIE) sponsored its second conference on materials research in low gravity at its annual International Symposium on Optical Science, Engineering, and Instrumentation. The symposium took place July 27-August 1, 1997, in San Diego, California. SPIE hopes to hold this conference every two years. The 1997 conference topics included materials for sensors and electronics with special emphases on crystal growth from the vapor phase, containerless processing of new materials, measurement of properties, and characterization

and modeling of crystal growth processes. A joint panel discussion on materials processing for detectors and electronics was also held in conjunction with other meetings with similar content at the symposium. The panel discussion outlined the current status of reduced-gravity materials processing and focused on the critical needs and challenges in this area. Researchers drawn from industry, universities, and various NASA centers presented papers in eight sessions and participated in the conference. Narayanan Ramachandran, of the Universities Space Research Association at MSFC, served as conference chairman and editor of the conference proceedings.

Flight Experiments

The LMD investigation utilized the Canadian vibration isolation system called the Microgravity Isolation Mount, which is located on the Russian space station, *Mir*. LMD was launched on the 81st Space Transportation System (STS-81) mission in January 1997 and was operated on *Mir* during the NASA-4 increment. The technological goals of LMD were to test the diffusion coefficient measurement technique at a single temperature using indium, and to determine how easily these diffusion coefficient measurements are contaminated by convection arising from g-jitter.

Seven materials science experiments were conducted on the MSL-1R mission in July 1997: Coarsening in Solid-Liquid Mixtures (CSLM); Liquid-Phase Sintering-2 (LPS-2); Diffusion Processes in Molten Semiconductors (DPIMS); Experiments on Nucleation in Different Flow Regimes; Alloy Undercooling Experiments; AC Calorimetry and Thermophysical Properties of Bulk, Glass-Forming Metallic Liquids; and Measurement of Surface Tension and Viscosity of Undercooled Liquid Melts.

The objective of the CSLM experiment was to study the coarsening kinetics of tin-rich particles in eutectic liquids of lead-tin alloys with various compositions. This study was conducted in order to gain an understanding of the coarsening process through direct comparison of the results from this experiment with current theories. The experiment was performed in an electric furnace in the shuttle's Middeck Glovebox.

The purpose of the LPS-2 experiment was to test theories regarding liquid-phase sintering and to examine coalescence and pore behavior during liquid-phase sintering in the microgravity environment. This investigation was conducted in the Japanese Large Isothermal Furnace (LIF), which is a vacuum-heating furnace designed to heat large samples uniformly.

The DPIMS experiment was designed to provide a definitive measurement of the diffusion coefficients of trace impurities such as gallium, silicon, and antimony in molten germanium, and to investigate the dependence of diffusion on temperature, impurity type, and sample diameter. These data will be used to develop models of diffusion. DPIMS was also conducted in the LIF.

The Experiments on Nucleation in Different Flow Regimes investigation was conducted in the German facility called TEMPUS

(Electromagnetic Containerless Processing Facility). The purpose of this investigation was to determine quantitatively the temperatures of solid nucleations from melts of pure zirconium and the number of nucleations at each temperature as the melts are cooled below their equilibrium freezing points under laminar and turbulent liquid flow conditions.

Alloy Undercooling Experiments also utilized the TEMPUS facility. The purpose of these experiments was to measure the solidification velocity in steel alloys using a combination of video and pyrometric techniques. These experiments were designed to yield information on phase selection and growth kinetics with limited melt convection. This work has direct application to the design of steel strip casting facilities on Earth and helps scientists understand how welding processes may be conducted in space.

The AC Calorimetry and Thermophysical Properties of Bulk, Glass-Forming Metallic Liquids investigation was conducted in the TEMPUS facility, and its purpose was to measure thermophysical properties of good, glass-forming metallic alloys to allow improvement of process technologies for such materials.

The Measurement of Surface Tension and Viscosity of Undercooled Liquid Metals investigation also utilized the TEMPUS facility. Its purpose was to demonstrate a containerless technique for measuring the viscosity and surface tension of reactive and undercooled liquid metals, such as zirconium; titanium; and metallic, glass-forming alloys.

The Isothermal Dendritic Growth Experiment (IDGE) is a fundamental microgravity materials science investigation that has been flown three times as part of the United States Microgravity Payload (USMP) series. Because virtually all industrially important alloys solidify from a molten state by a dendritic process, a fundamental understanding of dendritic solidification is necessary to correct mathematical models that will provide a basis for improved industrial production techniques. During the first two flights of IDGE on the shuttle, the IDGE flight hardware grew and photographed individual dendrites of the material succinonitrile as they solidified at various temperatures. The third flight of IDGE on USMP-4 will use a different sample material, pivalic acid.

The second flight of the Bismuth-Tin Solidification Experiment in the USMP series will provide data on the solidification behavior and the solid-liquid interface stability of bismuth and bismuth-tin alloys during crystal growth. The experiment uses the Seebeck technique to measure interface undercooling temperature, resistance change across the sample to measure interfacial velocity, Peltier pulsing for demarcation of the sample interface, and quenching to determine the chemistry and structure near the solid/liquid interface. This experiment will be carried out in the French-developed MEPHISTO furnace.

The second flight in the USMP series of the Growth of Solid-Solution Single Crystals experiment, using mercury cadmium telluride in the Advanced Automated Directional Solidification Furnace (AADSf), will produce material of high scientific value to

the electronics community. It is anticipated that this material will be of benchmark quality and suitable for advanced electrical property measurement. The effects of microgravity and the control of residual amounts of microgravity on crystal growth of materials having high alloy contents will be demonstrated.

The second flight in the USMP series of the Compound Semiconductor Crystal Growth in a Microgravity Environment investigation, using lead tin telluride in the AADSE, will establish some fundamental growth properties of lead tin telluride and a better understanding of the mechanisms involved in crystal growth, especially those affected by gravity. This information will not only help to produce better quality materials on Earth but will also help define future efforts of crystal growth in space and lead the way to an even deeper understanding of the most basic aspects of crystal growth.

The Particle Engulfment and Pushing by Solidifying Interfaces experiment will be conducted in the Middeck Glovebox (MGBX) as part of USMP-4. This investigation will obtain data that will aid in gaining a fundamental understanding of the interaction between

the solid-liquid interface of a solidifying material and particles interspersed in the material. Temperature, particle size, and furnace velocity data obtained from this investigation will be used to develop a theoretical basis for processing real-work composite materials.

The Wetting Characteristics of Immiscibles (WCI) experiment will also be conducted in the MGBX as part of USMP-4. The WCI investigation was designed to study ways to control the wetting behavior of immiscible liquids with the walls of their containers in order to produce more desirable structures. Because of the many useful characteristics of "immiscible alloys," there is great interest in producing combinations where the two liquids are uniformly distributed. When the liquid system can be controlled by processing in a microgravity environment, a better end product can be made.

The FY 1997 ground and flight tasks for materials science are listed in **Table 7**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Table 7 **Materials science tasks funded by the Microgravity Research Division in FY 1997**
(includes some continuing projects at no additional cost)

Flight Experiments

Coupled Growth in Hypermonotectics

J. Barry Andrews
University of Alabama, Birmingham, Birmingham, AL

Fundamental Aspects of Vapor Deposition and Etching Under Diffusion-Controlled Transport Conditions

Klaus J. Bachmann
North Carolina State University, Raleigh, NC

Experiments on Nucleation in Different Flow Regimes

Robert J. Bayuzick
Vanderbilt University, Nashville, TN

Investigation of the Relationship Between Undercooling and Solidification Velocity

Robert J. Bayuzick
Vanderbilt University, Nashville, TN

Equiaxed Dendritic Solidification Experiment

Christoph Beckermann
University of Iowa, Iowa City, IA

Alloy Undercooling Experiments in a Microgravity Environment

Merton C. Flemings
Massachusetts Institute of Technology, Cambridge, MA

Measurement of the Viscosity and Surface Tension of Undercooled Melts Under Microgravity Conditions and Supporting Magnetohydrodynamic Calculations

Merton C. Flemings
Massachusetts Institute of Technology, Cambridge, MA

Growth of Compound Semiconductors in a Low-Gravity Environment

Archibald L. Fripp
Langley Research Center, Hampton, VA

Gravitational Role in Liquid-Phase Sintering

Randall M. German
Pennsylvania State University, University Park, PA

Isothermal Dendritic Growth Experiment

Martin E. Glicksman
Rensselaer Polytechnic Institute, Troy, NY

Thermophysical Properties of Metallic Glasses and Undercooled Liquids

William L. Johnson
California Institute of Technology, Pasadena, CA

Orbital Processing of Eutectic Rod-Like Arrays

David J. Larson
State University of New York, Stony Brook, Stony Brook, NY

Orbital Processing of High-Quality Cadmium Telluride

David J. Larson
State University of New York, Stony Brook, Stony Brook, NY

Crystal Growth of II-VI Semiconducting Alloys by Directional Solidification

Sandor L. Lehoczký
Marshall Space Flight Center, Huntsville, AL

Growth of Solid-Solution Single Crystals

Sandor L. Lehoczký
Marshall Space Flight Center, Huntsville, AL

Diffusion Processes in Molten Semiconductors

David H. Matthiesen
Case Western Reserve University, Cleveland, OH

GaAs Crystal Growth Experiment

David H. Matthiesen
Case Western Reserve University, Cleveland, OH

The Study of Dopant Segregation Behavior During the Growth of GaAs in Microgravity

David H. Matthiesen
Case Western Reserve University, Cleveland, OH

Space- and Ground-Based Crystal Growth Using a Magnetically Coupled Baffle

Aleksandar G. Ostrogorsky
Rensselaer Polytechnic Institute, Troy, NY

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments

David R. Poirier
University of Arizona, Tucson, AZ

Self-Diffusion in Liquid Elements

Franz E. Rosenberger
University of Alabama, Huntsville, Huntsville, AL

Temperature Dependence of Diffusivities in Liquid Metals

Franz E. Rosenberger
University of Alabama, Huntsville, Huntsville, AL

Particle Engulfment and Pushing by Solidifying Interfaces

Doru M. Stefanescu
University of Alabama, Tuscaloosa, Tuscaloosa, AL

Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Physical Vapor Transport

Ching-Hua Su
Marshall Space Flight Center, Huntsville, AL

Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Vapor Transport

Ching-Hua Su
Marshall Space Flight Center, Huntsville, AL

Interface Pattern Selection Criterion for Cellular Structures in Directional Solidification

Rohit K. Trivedi
Iowa State University, Ames, IA

Coarsening in Solid-Liquid Mixtures

Peter W. Voorhees
Northwestern University, Evanston, IL

Vapor Growth of Alloy-Type Semiconductor Crystals

Heribert Wiedemeier
Rensselaer Polytechnic Institute, Troy, NY

Ground-Based Experiments

Analysis of Residual Acceleration Effects on Transport and Segregation During Directional Solidification of Tin-Bismuth in the MEPHISTO Furnace Facility

J. Iwan D. Alexander
University of Alabama, Huntsville, Huntsville, AL

Synthesis and Characterization of Single Macromolecules: Mechanistic Studies of Crystallization and Aggregation

Spiro D. Alexandratos
University of Tennessee, Knoxville, Knoxville, TN

Microgravity Impregnation of Fiber Preforms

M. Cengiz Altan
University of Oklahoma, Norman, OK

An Electrochemical Method to Visualize Flow and Measure Diffusivity in Liquid Metals

Timothy J. Anderson
University of Florida, Gainesville, FL

The Effect of Convection on Morphological Stability During Coupled Growth in Immiscible Systems

J. Barry Andrews
University of Alabama, Birmingham, Birmingham, AL

Foam Metallic Glasses

Robert E. Apfel
Yale University, New Haven, CT

Ostwald Ripening of Liquid and Solid Droplets in Liquid Metal Matrices

Alan J. Ardell
University of California, Los Angeles, Los Angeles, CA

Molecularly Tailored Surfaces via Self-Assembly Processes: Synthesis, Characterization, and Modeling

Mark A. Barteau
University of Delaware, Newark, DE

Dispersion Microstructure and Rheology in Ceramics Processing

John F. Brady
California Institute of Technology, Pasadena, CA

Combustion Synthesis of Materials in Microgravity

Kenneth Brezinsky
University of Illinois, Chicago, Chicago, IL

Application of Parallel Computing for Two- and Three-Dimensional Modeling of Bulk Crystal Growth and Microstructure Formation

Robert A. Brown
Massachusetts Institute of Technology, Cambridge, MA

Microstructure Formation During Directional Solidification of Binary Alloys Without Convection: Experiment and Computation

Robert A. Brown
Massachusetts Institute of Technology, Cambridge, MA

Modeling of Convection and Crystal Growth in Directional Solidification of Semiconductor and Oxide Crystals

Robert A. Brown
Massachusetts Institute of Technology, Cambridge, MA

Evolution of Crystal and Amorphous Phase Structure During Processing of Thermoplastic Polymers

Peggy Cebe
Tufts University, Medford, MA

Thermophysical Properties of High-Temperature Liquid Metals and Alloys

Ared Cezairliyan
National Institute of Standards and Technology, Gaithersburg, MD

Three-Dimensional Velocity Field Characterization in a Bridgman Apparatus: Technique Development and Effect Analysis

Soyoung Stephen Cha
University of Illinois, Chicago, Chicago, IL

Fundamental Studies of Solidification in Microgravity Using Real-Time X-Ray Microscopy

Peter A. Curreri
Marshall Space Flight Center, Huntsville, AL

Adaptive-Grid Methods for Phase Field Models of Microstructure Development

Jonathan A. Dantzig
University of Illinois, Urbana-Champaign, Urbana, IL

Atomistic Simulations of Cadmium Telluride: Toward Understanding the Benefits of Microgravity Crystal Growth

Jeffrey J. Derby
University of Minnesota, Minneapolis, MN

Combined Synchrotron White Beam X-Ray Topography and High-Resolution Triple Axis X-Ray Diffraction Characterization and Analysis of Crystals Grown in Microgravity and Ground-Based Experiments

Michael Dudley
State University of New York, Stony Brook, Stony Brook, NY

Use of Synchrotron White Beam X-Ray Topography for the Characterization of the Microstructural Development of Crystal – Normal Gravity Versus Microgravity

Michael Dudley
State University of New York, Stony Brook, Stony Brook, NY

Reverse Micelle-Based Synthesis of Microporous Materials in Microgravity

Prabir K. Dutta
Ohio State University, Columbus, OH

Studies on Nucleation, Polymerization, and Nanoparticle Composites in Supersaturated Vapors Under Microgravity Conditions

M. Samy El-Shall
Virginia Commonwealth University, Richmond, VA

Theoretical and Experimental Investigation of Vibrational Control of the Bridgman Crystal Growth Technique

Alexandre I. Fedoseyev
University of Alabama, Huntsville, Huntsville, AL

The Impaction, Spreading, and Solidification of a Partially Solidified Undercooled Drop

Merton C. Flemings
Massachusetts Institute of Technology, Cambridge, MA

Investigation of Local Effects on Microstructure Evolution

Donald O. Frazier
Marshall Space Flight Center, Huntsville, AL

Melt Stabilization of PbSnTe in a Magnetic Field

Archibald L. Fripp
Langley Research Center, Hampton, VA

Solidification of II-VI Compounds in a Rotating Magnetic Field

Donald C. Gillies
Marshall Space Flight Center, Huntsville, AL

Effect of Gravity on the Evolution of Spatial Arrangement of Features in Microstructure: A Quantitative Approach

Arun M. Gokhale
Georgia Institute of Technology, Atlanta, GA

Plasma Dust Crystallization

John A. Goree
University of Iowa, Iowa City, IA

Novel Directional Solidification Processing of Hypermonotectic Alloys

Richard N. Grugel
Universities Space Research Association,
Marshall Space Flight Center, Huntsville, AL

Utilizing Controlled Vibrations in a Microgravity Environment to Understand and Promote Microstructural Homogeneity During Floating-Zone Crystal Growth

Richard N. Grugel
Universities Space Research Association,
Marshall Space Flight Center, Huntsville, AL

Influence of Free Convection in Dissolution

Prabhat K. Gupta
Ohio State University, Columbus, OH

Microgravity Processing of Oxide Superconductors

William H. Hofmeister
Vanderbilt University, Nashville, TN

Dimensional Stability of Supermatrix Semiconductors

Douglas E. Holmes
Electronic Materials Engineering, Camarillo, CA

Nonequilibrium Phase Transformations

Kenneth A. Jackson
University of Arizona, Tucson, AZ

Physical Properties and Processing of Undercooled Metallic Glass-Forming Melts

William L. Johnson
California Institute of Technology, Pasadena, CA

Dislocation Formation During Growth of Semiconductor Crystals

Monica L. Kafeory
Case Western Reserve University, Cleveland, OH

The Role of Dynamic Nucleation at Moving Boundaries in Phase and Microstructure Selection

Alain S. Karma
Northeastern University, Boston, MA

Combined Heat Transfer Analysis of Crystal Growth

Mohammad Kassemi
Ohio Aerospace Institute, Cleveland, OH

Identification of Gravity-Related Effects on Crystal Growth From Melts With an Immiscibility Gap

Mohammad Kassemi
Ohio Aerospace Institute, Cleveland, OH

Measurement of Liquid-to-Solid Nucleation Rates in Undercooled Metallic Melts

Joseph L. Katz
Johns Hopkins University, Baltimore, MD

Fundamentals of Thermomigration of Liquid Zones Through Solids

Michael J. Kaufman
University of Florida, Gainesville, FL

Phase Formation and Stability: Composition and Sample-Size Effects

Kenneth F. Kelton
Washington University, St. Louis, MO

Influence of Natural Convection and Thermal Radiation on Multicomponent Transport and Chemistry in MOCVD Reactors

Anantha Krishnan
CFD Research Corporation, Huntsville, AL

Noise and Dynamical Pattern Selection in Solidification

Douglas A. Kurtze
University of Arizona, Tucson, AZ

Study of Magnetic Damping Effect on Convection and Solidification Under G-Jitter Conditions

Ben Q. Li
Washington State University, Pullman, WA

Quantitative Analysis of Crystal Defects by Triple Crystal X-Ray Diffraction

Richard J. Matyi
University of Wisconsin, Madison, Madison, WI

Numerical and Laboratory Experiments on the Interactive Dynamics of Convection, Flow, and Directional Solidification

Tony Maxworthy

University of Southern California, Los Angeles, CA

Y₂BaCuO₅ Segregation in YBa₂Cu₃O_{7-x} During Melt Texturing

Paul J. McGinn

University of Notre Dame, Notre Dame, IN

The Synergistic Effect of Ceramic Materials Synthesis Using Vapor-Enhanced Reactive Sintering Under Microgravity Conditions

John J. Moore

Colorado School of Mines, Golden, CO

Crystal Growth and Segregation Using the Submerged Heater Method

Aleksandar G. Ostrogorsky

Rensselaer Polytechnic Institute, Troy, NY

Gravitational Effects on the Morphology and Kinetics of Photo-Deposition of Polydiacetylene Films From Monomer Solutions

Mark S. Paley

Universities Space Research Association,

Marshall Space Flight Center, Huntsville, AL

Investigation of "Contactless" Crystal Growth by Physical Vapor Transport

Witold Palosz

Universities Space Research Association,

Marshall Space Flight Center, Huntsville, AL

Investigation of Convective Effects in Crystal Growth by Physical Vapor Transport

Witold Palosz

Universities Space Research Association,

Marshall Space Flight Center, Huntsville, AL

Analysis of Containerless Processing and Undercooled Solidification Microstructures

John H. Perepezko

University of Wisconsin, Madison, Madison, WI

Containerless Processing of Composite Materials

John H. Perepezko

University of Wisconsin, Madison, Madison, WI

Modeling of Detached Solidification

Liya L. Regel

Clarkson University, Potsdam, NY

Thermophysical Property Measurement of Molten Semiconductors in 1g and Reduced-Gravity Conditions

Won-Kyu Rhim

Jet Propulsion Laboratory, Pasadena, CA

Undercooling Limits and Thermophysical Properties in Glass-Forming Alloys

Won-Kyu Rhim

Jet Propulsion Laboratory, Pasadena, CA

Drop Tube Operation

Michael B. Robinson

Marshall Space Flight Center, Huntsville, AL

A Study of the Undercooling Behavior of Immiscible Metal Alloys in the Absence of Crucible-Induced Nucleation

Michael B. Robinson

Marshall Space Flight Center, Huntsville, AL

Determination of the Surface Energy of Liquid Crystals From the Shape Anisotropy of Freely Suspended Droplets

Charles S. Rosenblatt

Case Western Reserve University, Cleveland, OH

Modeling of Macroscopic/Microscopic Transport and Growth Phenomena in Zeolite Crystal Solutions Under Microgravity

Albert Sacco

Northeastern University, Boston, MA

Gravitational Effect on the Development of Laser Weld-Pool and Solidification Microstructure

Jogender Singh

Pennsylvania State University, University Park, PA

Flight Experiment to Study Double Diffusive Instabilities in Silver-Doped Lead Bromide Crystals

N. B. Singh

Northrop-Grumman Corporation, Pittsburgh, PA

Kinetics of Nucleation and Growth From Undercooled Melts

Frans A. Spaepen

Harvard University, Cambridge, MA

Magnetic Damping of Solid Solution Semiconductor Alloys

Frank R. Szofran

Marshall Space Flight Center, Huntsville, AL

The Features of Self-Assembling Organic Bilayers Important to the Formation of Anisotropic Inorganic Materials in Microgravity Conditions

Daniel R. Talham

University of Florida, Gainesville, FL

Dynamically Induced Nucleation of Deeply Supercooled Melts and Measurement of Surface Tension and Viscosity

Eugene H. Trinh

Jet Propulsion Laboratory, Pasadena, CA

A Proposal to Further Investigate the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber

James D. Trolinger

MetroLaser, Inc., Irvine, CA

Models of Magnetic Damping for Semiconductor Crystal Growth in Microgravity

John S. Walker

University of Illinois, Urbana-Champaign, Urbana, IL

Process-Property-Structure Relationships in Complex Oxide Melts

Richard Weber

Containerless Research, Inc., Evanston, IL

Thin Film-Mediated Phase-Change Phenomena: Crystallization, Evaporation, and Wetting

John S. Wettlaufer

University of Washington, Seattle, WA

Defect Generation in CVT Grown Hg_{1-x}Cd_xTe Epitaxial Layers Under Normal- and Reduced-Gravity Conditions

Heribert Wiedemeier

Rensselaer Polytechnic Institute, Troy, NY

Use of Microgravity to Control the Microstructure of Eutectics

William R. Wilcox

Clarkson University, Potsdam, NY

5 Acceleration Measurement

Overview

Acceleration measurement is the process by which knowledge of the microgravity environment is acquired, processed, analyzed, and passed on to the microgravity principal investigators (PIs). The PIs utilize this information during the interpretation of their science experiment results. Measuring the microgravity conditions of a microgravity science experiment is as crucial as measuring the temperature of a thermodynamics experiment. Accelerations (commonly interpreted as vibrations) cause disturbances such as convection, sedimentation, and mixing within microgravity science experiments.

Fluid motion, which is involved in most microgravity experiments, is strongly influenced by accelerations. In materials science experiments, for example, heavier elements, like mercury, tend to settle out of solution with steady accelerations. Hot gases in combustion experiments tend to move due to convection caused by low-frequency accelerations. Fluid movement due to accelerations may mask desired fluid characteristics, like surface tension, in some fluids experiments. Mechanical vibrations over a wide range of frequencies may cause drastic temperature changes in low-temperature physics experiments, where the samples are at temperatures close to absolute zero.

The primary objective of the acceleration measurement program is to characterize the reduced-gravity environment of the various experiment carriers, like the space shuttle; the Russian space station, *Mir*; sounding rockets; and the International Space Station, in order to provide useful information to scientists who conduct their experiments on such carriers. The Space Acceleration Measurement System (SAMS) has flown 18 missions since its first flight on the 40th Space Transportation System (STS-40) in 1991. SAMS units have flown in support of microgravity science experiments in the shuttle middeck, in the Spacelab module, on the Spacelab Mission Peculiar Experiment Support Structure, and in the SPACEHAB module. Experiments from all of the science disciplines have been supported on the shuttle. One SAMS unit was installed on *Mir* in 1994 and has been operated since then to support U.S. and Russian microgravity science and mechanical structure experiments.

The Orbital Acceleration Research Experiment (OARE) has flown 10 missions since its first flight on STS-40. The OARE instrument measures very low-frequency accelerations.

In fiscal year (FY) 1997, the inaugural mission involving the Space Acceleration Measurement System for Free Flyers (SAMS-FF) was conducted on a sounding rocket flight with a combustion experiment. A SAMS unit has also flown on the DC-9 reduced-gravity airplane to characterize the environment produced during parabolic flight on that facility. The acceleration measurement program has sponsored the flight of two European accelerometer systems to support the Life and Microgravity Spacelab (LMS) and Microgravity Science Laboratory (MSL)

missions. The Microgravity Measurement Assembly (MMA), developed by the European Space Agency (ESA), and the Quasi-Steady Acceleration Measurement instrument (QSAM), developed by the German Aerospace Research Establishment (DLR), were flown in FY 1996 and FY 1997.

The acceleration measurement program also works with other microgravity program participants, such as vibration isolation programs, to lend assistance with data processing, interpretation, and analysis. The information collected and produced by this program is available by means of mission summary reports, data files on CD-ROM and Internet file servers, and specialized analysis reports for scientists. Some of the highlights of the FY 1997 acceleration measurement program are discussed below:

- Data resulting from accelerometers aboard the LMS mission (STS-78) were analyzed, and a mission summary report was prepared to summarize the microgravity environment for that mission. The accelerometers aboard this mission were SAMS, OARE, and MMA. Processed and analyzed data were provided to the various experiment teams during and after the mission. A summary report describing the microgravity environment was prepared after the mission and provided to the PI teams and other mission participants.
- Data resulting from the SAMS in the SPACEHAB module on STS-79 during the space shuttle's docking with *Mir* were analyzed, and a mission summary report was prepared to summarize the microgravity environment. Processed and analyzed data were provided to the various experiment teams during and after the mission. A summary report describing the microgravity environment was prepared after the mission and provided to the PI teams and other mission participants.
- Data resulting from the SAMS on *Mir* were analyzed, and summary reports were prepared to characterize the microgravity environment on the station. Processed and analyzed data were provided to the various experiment teams. The acceleration measurement program has cooperated also with *Mir*'s Structural Dynamics Experiment and the Dynamic Load Sensors experiment.
- MSL-1 (STS-83) and MSL-1R (STS-94) were both supported with accelerometers and data processing and interpretation. The accelerometers aboard these missions were SAMS, OARE, MMA, and QSAM. Real-time data were received, processed, and interpreted during the mission to support the PI teams and their experiment operations. A summary report describing the microgravity environment was prepared after the mission and provided to the PI teams and other mission participants.
- Preparations have continued for the fourth United States Microgravity Payload (USMP-4) mission on STS-87.

On this mission, two SAMS instruments will provide acceleration measurements for four major experiments, and the OARE instrument will provide data about the low-frequency environment of the vehicle. A display on a crew computer will provide feedback about the microgravity environment to the crew.

Meetings

The Sixteenth Microgravity Measurements Group (MGMG) meeting was held in May 1997 at the University of Florida, Gainesville. This meeting was highlighted in an article in *Microgravity News*, vol. 4, no. 2. The annual MGMG meetings provide a forum for researchers involved in microgravity environment characterization to share the results of their work. The topics at this year's meeting were experimental results, vibration isolation, acceleration data evaluation, low-level gravity research, and new developments. The attendees this year included participants from space agencies, industry, and academia from Canada, the Czech Republic, France, Germany, Italy, Japan, the Netherlands, Russia, and the United States.

The Accelerations and Countermeasures in the Reduced Gravity Environment session of the 35th American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting was chaired by the acceleration measurement project scientist, Richard Delombard of Lewis Research Center. A panel session was also organized that brought together experts in vibration isolation to describe and discuss aspects of the Suppression of Transient Accelerations By Levitation experiment, the Active Rack Isolation System, and Microgravity Isolation Mount system.

Program personnel co-chaired two residual accelerations sessions at the Joint Xth European and VIth Russian Symposium on Physical Sciences in Microgravity conference in June 1997 in St. Petersburg, Russia.

A poster titled "Microgravity Environment Measurements and Analysis for PIs" was presented at the Gordon Research Conference on Gravitational Effects on Physico-Chemical Systems in July 1997 at New England College, Henniker, New Hampshire.

Flight Experiments

The 17th flight for a SAMS unit took place in the Spacelab module aboard the STS-83 mission as part of the first MSL payload. The OARE instrument was flown in the shuttle cargo bay on that same mission for its ninth flight. Both the SAMS and OARE instruments were again flown on the STS-94 reflight of the MSL payload for their 18th and 10th flights, respectively.

6 Technology and Hardware

Advanced Technology Development 1997

The Advanced Technology Development (ATD) Program was developed in response to the challenges researchers face when defining experiment requirements and designing associated hardware. Investing in technology development is necessary if the United States intends to remain a top competitor in future scientific research. ATD researchers help ensure that the nation continues its forward strides in the fields of technology development and scientific experimentation.

Technology development projects are designed to address scientific concerns, both focused and broadly based. Focused development projects ensure the availability of technologies that satisfy the science requirement of specific flight- or ground-based programs. Broadly based development projects encompass a long-term, proactive approach to meeting the needs of future projects and missions, such as the human exploration and development of space.

The Microgravity Research Division (MRD) solicits new ATD projects each year and selects the very best for funding. New ATD projects are solicited through a two-step process, for which NASA centers are eligible. First, concept papers are solicited from each NASA center involved in microgravity research. Next, the MRD director and ATD program manager form an ATD Review Panel consisting of microgravity science representatives from each NASA center and from the MRD program at NASA headquarters. The panel reviews concept papers for their technical merit and significance to the microgravity field, and selects candidates for further consideration.

These successful candidates must submit fully detailed ATD proposals. Proposals are peer-reviewed by experts in corresponding technology areas who are selected from non-NASA organizations. Final selections are made based on the panel's recommendations, which are based on relevance to the anticipated technology needs of the Microgravity Research Program, potential for success, and potential for the project to enable new types of microgravity investigations.

Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1997*, NASA Technical Memorandum 206645, February 1998.

Microgravity Technology Development Goals

The ATD Program is intended to provide efficient, cost-effective, and ongoing support for microgravity science investigations. The primary goal of the ATD Program is to develop technology that will enable new types of scientific investigation. This goal is achieved by enhancing the capabilities and quality of experiment hardware available to researchers and by overcoming existing technology-based constraints to microgravity science research capabilities. The ATD Program provides opportunities to carry out the goals of NASA's Microgravity Research Program by conducting state-of-the-art technology development.

MRD funds technology development through an initial feasibility demonstration that verifies whether or not a technology is suitable for use in either ground-based or flight programs. The goal is to investigate and develop high-risk microgravity research technologies before they are needed on the critical development path for actual flight hardware.

Depending on its state of maturity, the technology developed under the ATD Program may either make a direct transition to use in a specific ground-based or flight program, or require further development to satisfy a specific program requirement. Ideally, the successful progression or completion of an ATD task will reduce risk and cost in the transition from ground-based research to flight hardware design and application in the MRD.

Scope of Projects

Historically, ATD projects have encompassed a broad range of activities. Project funding includes the development of diagnostic instrumentation and measurement techniques, observational instrumentation and data recording methods, acceleration characterization and control techniques, and advanced methodologies associated with hardware design technology.

In fiscal year (FY) 1997, five NASA centers were involved in the MRD ATD Program: Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), Lewis Research Center (LeRC), and Marshall Space Flight Center (MSFC). The current projects, listed in **Table 8**, illustrate the breadth of technologies covered by the ATD Program.

Table 8 Current ATD projects

Magnetostrictive Low-Temperature Actuators

Robert Chave, JPL, Pasadena, California

The objective of this project is to further the development of low-temperature magnetostrictive materials. Reducing the cost and increasing the uniformity of magnetostrictive crystals will enhance potential applications. Future applications could include acoustic pumps for microgravity cryogen transfer or magnetometers that use magnetostrictive crystals as the primary sensor element and fiber optics for readout.

Advanced Heat Pipe Technology for Furnace Element Design in Spaceflight Applications

Donald Gillies, MSFC, Huntsville, Alabama

This project focuses on the development of a heat pipe that will operate as an isothermal furnace liner capable of processing materials at temperatures up to 1500° C (400° C higher than existing technology). The isothermality and tight control of the heat pipe will enable materials science experiments to be conducted under more favorable thermal conditions.

Space Bioreactor Bioproduct Recovery System

Steve Gonda, JSC, Houston, Texas

The purpose of this effort is to develop a Bioproduct Recovery System (BRS) that allows the selective removal of molecules of interest from space bioreactors, thus enhancing the productivity of those bioreactors. The BRS will be miniaturized to meet volume and power constraints, and designed to operate in microgravity.

Advanced Diagnostics for Combustion

Paul Greenberg, LeRC, Cleveland, Ohio

The goal of this project is to develop a series of more sophisticated measurement techniques applicable to the general area of microgravity combustion science in order to improve the accuracy and spatial/temporal yield of the data acquired, and to extend the range of applicability and access to the relevant parameters presently inaccessible through current methods.

Manufacturing of Refractory Containment Cartridges

Dick Holmes, MSFC, Huntsville, Alabama

This project focuses on using plasma spray in a low-pressure, inert environment to form containment cartridges to be used for growing crystals of metals, alloys, and semiconductors in microgravity.

Free-Float Trajectory Management

Kirk Logsdon, LeRC, Cleveland, Ohio

The objective of this work is to develop the technology for an extended, consistently reproducible acceleration environment during the stabilized low-gravity phase of the flight trajectory in DC-9 aircraft, specifically for free-float packages. The goals are to extend the free-float time to 10 seconds or longer and to obtain stable accelerations of 0.0001 g or lower in a consistent, reproducible manner.

Passive Free-Vortex Separator

John McQuillen, LeRC, Cleveland, Ohio

The objective of this project is to develop an effective, low-power, two-phase separation system. The system will enable the separation of two-phase flows for reuse during long-term spaceflight.

Laser Light Scattering With Multiple Scattering Suppression

William Meyer, LeRC, Cleveland, Ohio

This project provides a simple and novel optical scheme that overcomes multiple scattering effects in turbid media. In addition, ways to experimentally measure and provide a full analytical solution for double, triple, and higher-order scattering are being developed.

Surface Light Scattering

William Meyer, LeRC, Cleveland, Ohio

This project enables a new way of addressing surface sloshing that will allow the measurement of both surface tension and viscosity for transparent and optically accessible opaque media.

Laser-Feedback Interferometer

Ben Ovrzyn, LeRC, Cleveland, Ohio

The objectives of this ATD project are to evaluate, adapt, and deliver a novel form of interferometry, based upon laser-feedback techniques, that will provide a robust, versatile, state-of-the-art diagnostic instrument applicable to a wide variety of microgravity fluid physics and transport phenomena. The instrument can be used to measure both temporal and spatial change in optical path length and object reflectivity.

Development of an Electrostrictive Valve

David Pearson, JPL, Pasadena, California

The objectives of this ATD project are to develop a miniature cold valve with no moving parts for use as an active phase separator for liquid helium and to study the ability of a submicron aperture to act as a tunable Josephson junction in ^4He .

A Protein Crystal Growth Studies Cell

Marc Pusey, MSFC, Huntsville, Alabama

The primary goal of this project is to design and construct prototype cells and associated systems for the study of the protein crystal growth process. A second goal is to develop practical methods for storing proteins prior to use in crystal growth and other experiments.

High-Resolution Thermometry and Improved SQUID Readout

Peter Shirron, GSFC, Greenbelt, Maryland

The goal of this project is to develop high-resolution thermometers that overcome current problems such as radiation. A high-resolution penetration depth thermometer using a two-stage series array superconducting quantum interference device (SQUID) amplifier for readout will be more simple, cost-effective, and sensitive than existing technology.

Application of Superconducting Cavities to Microgravity Research

Don Strayer, JPL, Pasadena, California

This ATD project has two main objectives: (1) to use modern microwave electronics; high quality factor, low-temperature superconducting cavities; and high-resolution temperature control to develop an ultrastable oscillator system that will provide a comparison oscillator for the laser-cooled atomic oscillators now under development in the microgravity research program; and (2) to develop high-temperature superconductor materials, high quality factor cavities, and electronics that can be integrated with a small cryocooler to provide an easy-to-use materials characterization system for use on the International Space Station (ISS).

Determination of Soot Volume Fraction via Laser-Induced Incandescence

Randall Vander Wal, LeRC, Cleveland, Ohio

Laser-induced incandescence (LII) is being developed for microgravity combustion research as a two-dimensional imaging diagnostic for the measurement of soot volume fraction. LII, in conjunction with other optical imaging techniques, provides unparalleled temporal and spatial resolution, yielding insights into soot formation and oxidation processes.

Vibration Isolation and Control System for Small Microgravity Payloads

Mark Whorton, MSFC, Huntsville, Alabama

This project will deliver an active isolation device to provide a quiescent acceleration environment required for investigations to be carried out on the ISS.

A New Ultrahigh-Resolution Near-Field Microscope for Observation of Protein Crystal Growth

William Witherow, MSFC, Huntsville, Alabama

The primary objective of this ATD project is to build and test a new optical method for observing protein crystals as they nucleate and grow based on a tapered-fiber probe in a near-field scanning optical microscope.

Microgravity Technology Report

NASA's *Microgravity Technology Report* covers technology policies, development, and transfer activities within the Microgravity Research Program from FY 1978 through FY 1997. It also describes the recent major tasks initiated under the ATD Program and identifies current technology requirements. The *FY 1997 Microgravity Technology Report* is available as a companion to this annual MRP report.

Experiment Hardware for Space Shuttle and *Mir* Flights

Significant efforts continued in fiscal year 1997 in preparation of multiuser and experiment-unique apparatus for missions using the space shuttle and the Russian space station, *Mir*. Listed in **Table 9** are Space Transportation System (STS) missions with significant microgravity experiments, followed by short descriptions of the U.S.-developed flight experimental apparatus that have been in use and are under development in the Microgravity Research Program to support those missions. A list of flight experiment hardware being developed by international partners that will be used by U.S. investigators appears in **Table 10**.

Table 9 STS missions with major microgravity equipment on board, chronologically by launch date

Launch Date	Flight	Mission	Full Name
April 1985	STS-51B	SL-3	Spacelab-3
Jan. 1986	STS-61C		Materials Science Demonstrations
Jan. 1992	STS-41	IML-1	International Microgravity Laboratory-1
June 1992	STS-50	USML-1	United States Microgravity Laboratory-1
Oct. 1992	STS-52	USMP-1	United States Microgravity Payload-1
March 1994	STS-62	USMP-2	United States Microgravity Payload-2
July 1994	STS-65	IML-2	International Microgravity Laboratory-2
June 1995	STS-71	<i>Mir</i> -1	Shuttle/ <i>Mir</i> -1
July 1995	STS-70		Shuttle
Sept. 1995	STS-69	*	Wake Shield Facility, Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN)
Oct. 1995	STS-72	USML-2	International Microgravity Laboratory-2
Nov. 1995	STS-74	<i>Mir</i> -2	Shuttle/ <i>Mir</i> -2
Feb. 1996	STS-75	USMP-3	United States Microgravity Payload-3
March 1996	STS-76	<i>Mir</i> -3	Shuttle/ <i>Mir</i> -3
June 1996	STS-78	LMS	Life and Microgravity Spacelab
Sept. 1996	STS-79	<i>Mir</i> -4	Shuttle/ <i>Mir</i> -4
Jan. 1997	STS-81	<i>Mir</i> -5	Shuttle/ <i>Mir</i> -5
April 1997	STS-83	MSL-1	Microgravity Science Laboratory-1
May 1997	STS-84	<i>Mir</i> -6	Shuttle/ <i>Mir</i> -6
July 1997	STS-94	MSL-1R	Microgravity Science Laboratory-Reflight
Aug. 1997	STS-85		CRISTA-SPAS-2, Japanese Experiment Module Flight Demonstration
Sept. 1997	STS-86	<i>Mir</i> -7	Shuttle/ <i>Mir</i> -7
Nov. 1997	STS-87	USMP-4	United States Microgravity Payload-4
Jan. 1998	STS-89	<i>Mir</i> -8	Shuttle/ <i>Mir</i> -8
March 1998	STS-90		Neurolab
Feb. 2001	STS-113	MSP-1	Microgravity Science Payload-1

* *Middeck and Get Away Special (GAS) microgravity payloads only. GAS payloads also flew on STS-40, -41, -43, -45, -47, -54, -57, -60, -63, -64, -66, -72, and -77.*

Advanced Automated Directional Solidification Furnace: This instrument is a modified Bridgman-Stockbarger furnace for directional solidification and crystal growth. (USMP-2, USMP-3, USMP-4)

Bioreactor Demonstration Unit (BDU): The BDU is a rotating cylinder bioreactor that is supported by subsystems that provide media perfusion and exchange, incubator temperature control, and data storage. It is useful for the investigation of cell science and tissue engineering. (STS-70, Shuttle/Mir-4, Shuttle/Mir-8)

Biotechnology Refrigerator (BTR): The BTR has a refrigerated volume of 0.58 cubic feet with forced air convection. It is programmable with a temperature range of 4° C to 50° C. (Shuttle/Mir-7, Shuttle/Mir-8, Neurolab)

Biotechnology Specimen Temperature Controller (BSTC): BSTC is a programmable cell culture incubator that can be used for flight experiments in cell biology, microbiology, and tissue engineering. The current version has four individually controlled chambers with a temperature range of 4° C to 50° C. (Shuttle/Mir-7, Neurolab)

Biotechnology System: This instrument is composed of a rotating wall vessel bioreactor, a control computer, a fluid supply system, and a refrigerator for sample storage. (*Mir*)

Combustion Module-1: This module is being developed to perform multiple combustion experiments in orbit; the first two experiments were the Laminar Soot Processes experiment and the Structure of Flameballs at Low Lewis Number experiment. (MSL-1, MSL-1R)

Confined Helium Experiment Apparatus: This apparatus provides a thermometer resolution better than 100 picodegrees in measuring properties of helium samples confined to a two-dimensional state. It flew in the Low-Temperature Platform, where it was used to test finite size effects under controlled conditions to uncover underlying fundamental principles. (USMP-4)

Critical Fluid Light Scattering Experiment Apparatus: This apparatus provides a microkelvin-controlled thermal environment for performing dynamic light scattering and turbidity measurements of room-temperature critical fluids. (USMP-2, USMP-3)

Critical Viscosity of Xenon Experiment Apparatus: This apparatus provides a precision-controlled thermal environment (microkelvin) and an oscillating screen viscometer to perform viscosity measurements of room-temperature critical fluids. (STS-85)

Crystal Growth Furnace: This instrument is a modified Bridgman-Stockbarger furnace for crystal growth from a melt or vapor. (USML-1, USML-2)

Diffusion-Controlled Protein Crystallization Apparatus for Microgravity (DCAM): The DCAM hardware, which was designed for long-duration protein crystal growth on *Mir*, combines liquid-liquid diffusion and dialysis methods to effect protein crystal growth. Each DCAM tray assembly consists of 27 DCAM experiment chambers containing precipitant solutions and protein sample solutions. (Shuttle/Mir-4, Shuttle/Mir-5, Shuttle/Mir-6)

Drop Physics Module: This apparatus is designed to investigate the surface properties of various suspended liquid drops, to study surface and internal features of drops that are being vibrated and rotated, and to test a new technique for measuring the surface tension between two immiscible fluids. (USML-1, USML-2)

Droplet Combustion Experiment Apparatus: This apparatus is designed to study droplet behavior during combustion by measuring burning rates, extinction phenomena, disruptive burning, and soot production. (MSL-1, MSL-1R)

Gas Supply Module (GSM): The GSM provides a carbon dioxide-enriched air supply for the support of mammalian cell culture in the bioreactors. (Shuttle/Mir-4, Shuttle/Mir-8)

Gaseous Nitrogen (GN₂) Dewar Protein Crystal Growth Experiment Apparatus: The GN₂ dewar is a device that can maintain samples at cryogenic temperatures for about 13 days. Frozen liquid-liquid diffusion and batch protein crystal growth experiments are launched in a GN₂ dewar and then allowed to thaw to initiate the crystallization process in a microgravity environment. The GN₂ dewar houses a protein crystal growth insert that typically holds approximately 200 protein samples. (Shuttle/Mir-4, Shuttle/Mir-5, Shuttle/Mir-6)

Geophysical Fluid Flow Cell: This instrument uses electrostatic forces to simulate gravity in a radially symmetric vector field, centrally directed toward the center of the cell. This allows investigators to perform visualizations of thermal convection and other research-related topics in planetary atmospheres and stars. (Spacelab-3, USML-2)

Interferometer for Protein Crystal Growth (IPCG): The IPCG is an apparatus designed to operate in the *Mir* glovebox to measure details of how protein molecules move through a fluid and then form crystals. IPCG comprises three major systems designed to produce images showing density changes in a fluid as a crystal forms: an interferometer, six fluid assemblies, and a data system. (Shuttle/Mir-7)

Isothermal Dendritic Growth Experiment Apparatus: This apparatus is being used to study the growth of dendritic crystals in transparent materials that simulate the solidification of some aspects of pure metals and metal alloy systems. (USMP-2, USMP-3, USMP-4)

Lambda Point Experiment Apparatus: This apparatus provides temperature control in the part-per-billion range of a bulk helium sample near the superfluid transition at 2 K for testing the theory of critical phenomena under well-controlled static conditions. It flew in the Low-Temperature Platform. (USMP-1)

Low-Temperature Microgravity Physics Cryogenic Dewar: This apparatus supports different experiments, including the Lambda Point Experiment, the Confined Helium Experiment, and the Critical Dynamics in Microgravity experiment. (USMP-4, MSP-1)

Low-Temperature Platform: This apparatus provides a 2 K environment for fundamental physics experiments for up to 12 days on the shuttle. It also provides the mechanical and data interfaces between the experiment and the shuttle carrier. The apparatus supported the Lambda Point Experiment and the Confined Helium Experiment. (USMP-1, USMP-4)

Mechanics of Granular Materials Experiment Apparatus: This instrument uses microgravity to gain a quantitative understanding of the mechanical behavior of cohesionless granular materials under very low confining pressures. (Shuttle/Mir-4, Shuttle/Mir-8)

Microgravity Glovebox: This is a modified middeck glovebox designed for *Mir* that will enable the collection of scientific and technological data prior to major investments in the development of more sophisticated scientific instruments. (*Mir*)

Microgravity Smoldering Combustion Apparatus: This apparatus is used to determine the smoldering characteristics of combustible materials in microgravity environments. (STS-69)

Middeck Glovebox: The glovebox is a multidisciplinary facility used for small scientific and technological investigations. (USMP-3, USMP-4, MSP-1)

Orbital Acceleration Research Experiment Apparatus: This instrument is developed to measure very low-frequency accelerations on orbit such as atmospheric drag and gravity gradient effects. (Multiple missions)

Physics of Hard Spheres Experiment Apparatus: This hardware supports an investigation studying the processes associated with liquid-to-solid and crystalline-to-glass phase transitions. (MSL-1, MSL-1R)

Pool Boiling Experiment Apparatus: This apparatus is capable of autonomous operation for initiating, observing, and recording nucleate pool boiling phenomena. (Multiple missions)

Protein Crystallization Apparatus for Microgravity (PCAM): The PCAM is used to evaluate the effects of gravity on vapor diffusion protein crystal growth and to produce improved protein crystals in microgravity for determination of molecular structures. Each PCAM cylinder contains 9 crystallization plates, each having 7 sample chambers, for a total of 63 chambers per cylinder. The total number of samples that can be flown in a Single-Locker Thermal Enclosure System unit is 378. (MSL-1, MSL-1R, STS-85)

Second-Generation Vapor Diffusion Apparatus (VDA-2): The VDA-2 trays are protein crystal growth devices based on a syringe assembly design to provide mixing of protein and precipitant solutions in microgravity. A mixing chamber (third barrel) has been added to the original double-barreled VDA syringes to improve mixing during activation of vapor diffusion protein crystal growth flight experiments. A Single-Locker Thermal Enclosure System (STES) can accommodate four VDA-2 trays. Each VDA-2 tray has 20 sample chambers, for a total of 80 samples per STES. (MSL-1, MSL-1R, Shuttle/Mir-6)

Single-Locker Thermal Enclosure System: The STES replaces a single middeck locker and provides a controlled temperature environment within plus or minus 0.5° C of a set point in the range from 4° C to 40° C. The STES houses a variety of protein crystal growth experiment apparatus, including the PCAM and VDA-2. (MSL-1, MSL-1R, Shuttle/Mir-6)

Solid Surface Combustion Experiment Apparatus: This instrument is designed to determine the mechanism of gas-phase flame spread over solid fuel surfaces in the absence of buoyancy-induced or externally imposed gas-phase flow. (Multiple missions)

Space Acceleration Measurement System (SAMS): SAMS measures and records the acceleration environment in the space shuttle middeck and cargo bay, in the Spacelab, in SPACEHAB, and on *Mir*. (Multiple missions)

Surface Tension-Driven Convection Experiment Apparatus: This apparatus is designed to provide fundamental knowledge of thermocapillary flows and fluid motion generated by surface tension and temperature gradients along a free surface. (USML-1, USML-2)

Transitional/Turbulent Gas Jet Diffusion Flames Experiment Apparatus: This instrument is used to study the role of large-scale flame structures in microgravity transitional gas jet flames. (Get Away Special Experiment)

Table 10 Flight experiment hardware developed by international partners and used by NASA's Microgravity Research Program

Advanced Gradient Heating Furnace	European Space Agency (ESA)
Advanced Protein Crystallization Facility	ESA
Biolab	German Aerospace Research Establishment (DLR)
Bubble, Drop, and Particle Unit	ESA
Critical Point Facility	ESA
Cryostat	DLR
Electromagnetic Containerless Processing Facility (TEMPUS)	DLR
Electrophoresis, Recherché Appliqué sur les Methods de Separation en Electrophorese Spatiale (RAMSES)	French National Center for Space Studies (CNES)
Free Flow Electrophoresis Unit	National Space Development Agency of Japan (NASDA)
Gloveboxes*	ESA
Large Isothermal Furnace	NASDA
Apparatus for Studying Interesting Solidification Phenomena on Earth and in Space (MEPHISTO)	CNES
Microgravity Isolation Mount	Canadian Space Agency (CSA)
Microgravity Measurement Assembly	ESA
Mirror Furnace	NASDA
Quasi-Steady Acceleration Measurement	DLR

* *Middeck Glovebox, Microgravity Glovebox*

Space Station Facilities for Microgravity Research

The Microgravity Research Program (MRP) continues to develop several multiuser facilities specifically designed for long-duration scientific research aboard the ISS. To obtain an optimal balance between science capabilities, costs, and risks, facility requirements definitions have been aligned with evolving space station capabilities. In total, the MRP has now defined requirements for five multiuser facilities for the ISS:

- Biotechnology Facility (BTF).
- Fluids and Combustion Facility (FCF).
- Low-Temperature Microgravity Physics Facility (LTMPPF).
- Materials Science Research Facility (MSRF).
- Microgravity Science Glovebox (MSG).

The BTF will accommodate systems to address cell growth, tissue engineering, protein crystal growth, and fundamental biotechnology research using the microgravity environment and the extended mission time of the space station. In addition, this facility will handle the hardware for new areas of biotechnology research that are being explored. Due to funding limitations, it was decided to use the capabilities of the EXPedite Processing of Experiments to Space Station (EXPRESS) rack facility to handle the needs of biotechnology research during the early phases of the

space station. The development of the BTF as a facility dedicated to meet the comprehensive needs of biotechnology researchers has been delayed to a later phase in the space station's operational life.

The FCF will be a permanent on-orbit facility located inside the U.S. Laboratory Module of the ISS. The FCF will support NASA Human Exploration and Development of Space microgravity program objectives. In particular, the FCF will accommodate and facilitate sustained, systematic microgravity fluid physics and combustion science experimentation on the ISS for the lifetime of the ISS, defined as 10 years with an option to extend to 15 years.

The FCF is being developed predominantly in-house by Lewis Research Center, which also has responsibility for the management of NASA's microgravity fluid physics and combustion science programs. The FCF capabilities and development schedule have been tightly integrated with the scientific needs and schedules of these programs. As a consequence, the most promising principal investigators (PIs) currently funded by NASA have been scheduled to FCF availability beyond the year 2004 — a PI's actual flight date will be determined at a later date, based on merit. This integrated approach assures the maximum scientific relevancy and return at the lowest cost.

The FCF held its concept design review (CoDR) in December 1994 and its requirements definition review (RDR)

in October 1996. Since the CoDR, the projected development cost of the FCF has been cut in half while the projected scientific productivity has been more than doubled. Compared to NASA-funded microgravity fluids and combustion experiments on the space shuttle, ISS FCF experiments will cost about one-fifth to one-third as much to build. The FCF requires three on-orbit racks working together to get the necessary economies.

During FY 1997, the RDR hardware concept was substantially revised to allow the three FCF racks to be launched at intervals of approximately one year. In 2001, a Combustion Integrated Rack will be launched, followed by a Fluids Integrated Rack in 2002 and a Shared Accommodations Rack in 2003. At that time, equipment will be moved among the three racks to create the originally envisioned three-rack FCF system, which will perform the full range of fluids and combustion experiments. The FCF project will be operating with a minimal staff through at least 1998.

The LTMPF project combined minimal resources at investigator, industry, and JPL facilities into subteams of adequate size to deliver value-added products in FY 1997. The combined definition team is generating the infrastructure for developing ISS-era instrument requirements through fast prototyping/testing cycles. The test infrastructure, including an instrumented, shakable, cryogenic system, was completed in FY 1997. Development of a laboratory version of the LTMPF electronics controller was started in partnership with Stanford University. A LTMPF CoDR was tentatively scheduled for the end of FY 1998. The Critical Dynamics in Microgravity experiment was added as an LTMPF flight experiment candidate in August 1997, and it is expected that two additional flight definition investigations may be selected from 1996 NASA Research Announcement proposals.

The MSRF is designed to support the current and evolving group of U.S. peer-selected investigations. It will provide the facilities for satisfying near-term and long-range materials science program goals and objectives in a microgravity environment on the ISS. The MSRF consists of a multiple array of modular Materials Science Research Racks (MSRRs) designed to accommodate investigations in basic materials research, applications, and studies of phenomena involved in solidification of metals and crystal growth studies of various semiconductor materials. These investigations require sustained, systematic research and development to identify and characterize the effects of reduced gravity.

The modular racks will support materials science investigations in the U.S. Laboratory Module of the ISS. Each MSRR is a stand-alone, autonomous rack and will be comprised of experiment modules that can be replaced on orbit; module inserts; and investigation-unique apparatus and/or multiuser, generic processing apparatus that will support a wide variety of scientific investigations. The first MSRR (MSRR-1) planned for the ISS is being developed collaboratively by NASA and ESA, and is scheduled for launch on UF-3 in late 2001.

The NASA/ESA accommodations will occupy up to half of a rack, with the remainder of the rack dedicated to NASA.

Inserts will house the sample or sample cartridge, will contain heating elements, and can be changed out on orbit. They are envisioned for Bridgman-type crystal growth, isothermal applications, and a variety of other experiments. MSRR-2 and subsequent racks will satisfy investigations that have specific or unique facility requirements that cannot be satisfied with an insert.

The NASA/ESA accommodations definition is in Phase B, with Phase B completion planned for February 1998. An international Materials Science Workshop was held October 13–14, 1997, in Rome, Italy. The workshop provided a forum to continue dialogue between international partners on cooperative development and sharing of research facilities.

The MSG is a multidisciplinary facility for small, low-cost, rapid-response scientific and technological investigations in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science, allowing preliminary data to be collected and analyzed prior to any major investment in sophisticated scientific and technological instrumentation. Negotiations with ESA have been completed for the provision of the MSG by ESA in exchange for early access to ISS capabilities. The MSG completed its preliminary design review in April 1997, and will begin the critical design review process in January 1998. Deployment of the MSG to the ISS is tentatively planned for UF-2 in March 2000.

Ground-Based Microgravity Research Support Facilities

During FY 1997, NASA continued to maintain very productive reduced-gravity research ground facilities that include a drop tower, a drop tube, DC-9 and KC-135 parabolic flight aircraft, the Zero Gravity Facility, and several other facilities in support of the MRP. These facilities provide a unique and critical infrastructure necessary for the execution of the many flight- and ground-based investigations and experiments discussed in this report. The reduced-gravity facilities at LeRC have supported numerous investigations addressing various processes and phenomena in several research disciplines for the past 30 years. LeRC's drop tower and a DC-9 aircraft are able to provide a low-gravity environment (gravitational levels that range from 0.01 of Earth's gravitational acceleration to 0.0001 of that measured at the Earth's surface) for brief periods of time. "Zero gravity," or near weightlessness, also known as microgravity, can be created in these facilities by executing a freefall or semi-freefall condition where the force of gravity on an object is offset by its linear acceleration during a "fall" (a drop in a tower or a parabolic maneuver by an aircraft). The low-gravity environment obtained "on the ground" in the NASA facilities is similar to that of a spacecraft in an orbit around the Earth. Even though ground-based facilities offer relatively short experiment times of a few to 20 seconds, this available test time has been found to be sufficient to advance the scientific understanding of many phenomena. Also, many experiments scheduled to fly on sounding rockets, the fleet of space shuttles,

Space Station *Mir*, and the International Space Station are tested and validated in the ground facilities prior to testing in space. Experimental studies in a low-gravity environment can provide new discoveries and advance the fundamental understanding of science. Many tests performed in the NASA facilities, particularly in the disciplines of combustion science and fluid physics, have resulted in exciting findings that are documented in a large body of literature.

The LeRC facilities host scientists and engineers, both domestic and foreign, from universities and government agencies. Typically, on an annual basis, well over 100 microgravity experiments are supported by these unique national resources. The following information highlights the accomplishments of these facilities in FY 1997.

Able to accommodate several experiments during a single flight, LeRC's DC-9 aircraft represents the largest ground-based, reduced-gravity platform. Low-gravity conditions of approximately 20 seconds can be obtained by flying a parabolic trajectory that includes a rapid climb at about 55–60 degrees, a slow pushover at the top of the climb, and a descent angle of about 30–40 degrees. During the course of this maneuver, an altitude change of approximately 6000 feet is experienced. Over 50 of these maneuvers can be performed on a single flight.

The DC-9 continued to play a key role in microgravity research in FY 1997. The aircraft flew 73 flights with 3,313 trajectories accomplished in 180 flight hours. Thirty-eight investigations were supported, many of which flew multiple times. Some of the key highlights included astronaut crew training for several experiments that flew on MSL-1 and MSL-1R. Also, the president of the CSA, William Evans; and the Canadian Minister of Industry, John Manly, participated in research flights that had CSA-sponsored experiments on board. These milestones were all reached prior to July 21, at which time the DC-9 was eliminated from the microgravity program. Future reduced-gravity aircraft flights will be performed on JSC's KC-135 aircraft. Six to 12 flight campaigns will be conducted out of LeRC every year with this aircraft. In FY 1997, four experiments were performed during 223 trajectories over 10.9 flight hours.

The LeRC 2.2-Second Drop Tower obviously offers a shorter test time than the DC-9 or KC-135, but its simple mode of operation and capability of performing several tests per day make it an attractive and highly utilized test facility, particularly for performing evaluation and feasibility tests. Over 16,000 tests have been performed in the drop tower to date. During FY 1997, as in the past several years, drop tests averaged about 100 per month.

Reduced-gravity conditions in the drop towers are created by dropping an experiment in an enclosure, known as a drag shield, to isolate the test hardware from aerodynamic drag during a 24-m freefall in the open environment. Over 30 experiments were supported during the 1,200 drops performed in FY 1997. As in the past, several of these experiments were in support of the development of space shuttle experiments. The steady utilization of the drop tower is expected to continue as many new experiments are in the design and fabrication phases of development for the coming years.

The Zero Gravity Research Facility at LeRC, a registered U.S. national landmark, provides a quiescent low-gravity environment for a test duration of 5.18 seconds as experiments are dropped in a vacuum chamber that goes 132 m underground. Aerodynamic drag on the freely falling experiment is nearly eliminated by dropping in a vacuum. This procedure restricts drop tests to two per day, resulting in fewer projects supported in this facility. However, the relatively long test time and excellent low-gravity conditions more than compensate for the lower test throughput rate. In FY 1997, seven major projects were supported as 130 test drops were executed.

The Drop Tube Facility, located at MSFC, consists of sections of a 26-cm diameter stainless steel pipe vertically assembled into a tube of 105 m in length. Completely evacuated of air, the tube can produce freefall periods of 4.6 seconds. Vacuum levels of less than a billionth of an atmosphere are achievable. The drop tube is especially useful for high-temperature material processing assays, as well as experiments in droplet dynamics and engineering tests such as the ones designed to yield results for the Tethered Satellite Mission. In FY 1997, six experiments were supported during 351 drops.

Table 11 summarizes activities at ground-based microgravity research facilities in FY 1997.

Table 11 Use of ground-based low-gravity facilities in FY 1997

	Zero Gravity Facility	2.2-Second Drop Tower	Drop Tube Facility	KC-135	DC-9
Number of investigations supported	7	30	6	4	38
Number of drops or trajectories	130	1,200	351	223	3,313
Number of flight hours	N/A	N/A	N/A	10.9	180

7 Education and Outreach Activities

Once again, thousands of elementary and secondary school teachers attended the 1997 annual meetings of the National Science Teachers Association, the National Council of Teacher's of Mathematics, and the International Technology Education Association. These educational meetings and conferences provide NASA with the opportunity to demonstrate new ways to improve student understanding of the effects of normal and low gravity and the implications of microgravity research. Over 10,000 each of microgravity science educational posters, teacher's guides, mathematics briefs, reduced-gravity demonstrator manuals, microgravity mission lithographs, and other supplementary materials were distributed at the conferences. The number of teachers requesting to be added to the microgravity education and outreach mailing list was 1,483, compared to 1,200 last year. With these new additions, the total number of K–12 teachers on the mailing list is 3,321 (726 kindergarten and elementary, 826 middle school, 1,473 high school, and 296 other educators.)

The microgravity research centers — the Jet Propulsion Laboratory (JPL), Lewis Research Center (LeRC), and Marshall Space Flight Center (MSFC) — also participated in various regional and national outreach/educational and media activities. These activities included open houses at JPL and MSFC, where over 10,000 citizens at each location visited the centers and laboratories to learn, through demonstrations provided by microgravity scientists and engineers, about the microgravity research being conducted; the Apple MacWorld Conference, where data acquisition software was used on a Macintosh computer to demonstrate how an experimental procedure can be controlled and data can be acquired and displayed remotely using the Internet; television/radio interviews by local and national networks during the first Microgravity Science Laboratory (MSL–1) mission in July 1997; newspaper and talk show interviews, including appearances on “Good Morning America” and “The Phil Donahue Show”; a tour of a Ford Motor Company plant, where researchers from LeRC spoke with attendees of the American Institute of Aeronautics and Astronautics conference about engineering issues; creation of videos and web sites highlighting microgravity research; cooperative educational activities with programs such as the Caltech Precollege Science Initiative (CAPSI), which helped to develop a middle school science module; and hosting high school students who were winners of the Space Science Student Involvement Program competition.

The Microgravity Research Program's (MRP's) quarterly newsletter, *Microgravity News*, continues to reach thousands of K–12 teachers, curriculum supervisors, science writers, university faculty, graduate students, scientists and principal investigators, and technology developers. Distribution for each newsletter has reached an all-time high of 9,082 copies, which is an increase of 275 percent. In addition to individuals receiving the *Microgravity News*, distribution to public and private associations, corporations, laboratories, and education resource centers continues to grow. *Microgravity News* features articles on experiment results, shuttle missions, science and technology developments, research funding opportunities, meetings, collaborations, and microgravity science researchers.

From a national pool of 35 applicants, 7 graduate students were selected to receive support for ground-based microgravity research during 1997–1998 under the Graduate Student Research Program (GSRP). These selections were made from a pool of applicants who submitted their research proposals to NASA headquarters. Each of the microgravity research centers also selects graduate students who will conduct a portion of their research at a NASA research facility. All selections were based on a competitive evaluation of academic qualifications, proposed research plans, and the students' projected use of NASA and/or other research facilities. The new selections for 1997–1998 have brought the number of GSRP researchers to 20. When added to the graduate students working with NASA-funded PIs, the number of graduate students directly employed in microgravity research now totals 748.

The MRP's World Wide Web (WWW) Home Page continues to provide regular updates on upcoming conferences, microgravity-related research announcements, enhanced links to microgravity research centers, educational links, and links to microgravity science photo/image archives. A list of important microgravity WWW Internet addresses is presented in **Table 12**.

The JPL fundamental physics team has remained actively engaged in reaching out to explain and demonstrate the microgravity program to the community. The following examples illustrate the many ways in which the team continues to demonstrate a strong commitment to making microgravity research available and relevant through public outreach, educational involvement, and cross-discipline participation.

The Microgravity Scaling Theory Experiment (MISTE) project, headed by Principal Investigator Martin Barmatz, of JPL, participated in the Apple MacWorld Conference in San Francisco, California, January 7–10, 1997. Labview data acquisition software was used on a Macintosh computer to demonstrate how an experimental procedure can be controlled and data can be acquired and displayed remotely using the Internet. The MISTE project also had a booth at the conference where a poster was displayed and handouts were given to the public describing this NASA low-temperature microgravity fundamental physics experiment. The attendance at MacWorld was approximately 70,000 people. The demonstrations proved to be very good examples of public outreach and demonstrated JPL's use of advanced technology. Senior Apple executives also witnessed the demonstrations and actively participated in controlling the experiment. The conference attendees who saw the demonstrations were favorably impressed. The MISTE team is following up this conference presentation and producing technology development agreements with National Instruments, the company that markets the Labview software, as the industrial partner.

JPL introduced students to science by bringing middle school, high school, and college students into its laboratories. A middle school honor class toured the low-temperature physics lab building, and the students and teachers were shown demonstrations of cryogenic phenomena. The students also visited research sites,

where the goals of several investigations were described by JPL scientists.

Members of the Low-Temperature Science and Engineering group (LTSE) at JPL remain actively involved in outreach activities. During the past year, several of the group members have taken cryogenic demonstration kits into grade school classrooms to show students the behavior of materials at low temperatures. The LTSE group participated in the JPL Open House in June, and plans are presently being devised for participation in the Los Angeles County Fair in September.

A new educational activity began this year in cooperation with the CAPSI program to develop a middle school science module. Since our research program explores gravity-related physical phenomena, the first module will describe how gravity affects the behavior of fluids. Scientists from JPL will work with middle school teachers to develop materials that the students will use in an inquiry-based learning method. Larry Wade is to be commended for his initiative in contacting the CAPSI organization to begin this educational pursuit.

The LTSE group also hosted seven college students and one high school student as summer hires in JPL labs this past summer. The students worked on computer programs using the Labview operating system, on designing hardware and lab space organization, and on building magnetostrictive devices for cryogenic applications. One Caltech student will continue his association with fundamental physics through a senior thesis studying limits of time system coordination with various techniques, such as the Global Positioning System.

Microgravity Data Archiving

MSFC maintains the Microgravity Science Data Archive, which houses video, photographic, digital, and other data products generated during microgravity biotechnology and materials science experiments. Information concerning these experiments and their data products is contained in approximately 75 Experiment Data Management Plans (EDMPs). In addition to the EDMPs, further information concerning microgravity experiments in all microgravity science disciplines resides in the Microgravity Research Experiments (MICREX) database, which currently contains over 900 experiment records. In the future it will be possible to search the MICREX database and the European Space Agency's (ESA's) Microgravity Database simultaneously. In addition, there are plans to add other international partner databases to allow access to all existing microgravity databases.

The MSFC photo archive contains approximately 4,500 photographs. In FY 1997, a subset of over 200 of these images was digitized and made available through the Microgravity Research Program WWW site at <http://microgravity.msfc.nasa.gov>. Over 350 videotapes and 16-mm films are cataloged in the MSFC video archive.

LeRC has been actively building its archive collection in the areas of combustion science and fluid physics. Currently, there

are over 710 combustion science papers and over 435 fluid physics papers in the archive; a listing of the papers by author, along with abstracts from the papers, is available at <http://www.lerc.nasa.gov/WWW/MCFEP>. In FY 1997, abstracts of the papers continued to be added to the LeRC WWW site. The experiments database currently consists of information from a number of recent experiments, along with data from a few earlier missions. This information is contained in an EDMP database and includes such items as an experiment description; a list of publications associated with the experiment; a summary of experiment results and data; and a listing of videos, photos, and digital data. In FY 1997, archivists continued gathering data on fluids and combustion experiments from missions prior to the first United States Microgravity Laboratory (USML-1). They also began gathering data from missions after USML-1. Several of the EDMPs are available on the LeRC web site. The EDMPs for all fluid physics and combustion science experiments flown will continue to be collected and added to the LeRC web site in FY 1998. Photographs from the experiments will also be added to the database during FY 1998.

Table 12 Important Microgravity WWW Sites

NASA Home Page

Information and links to all NASA centers
<http://www.nasa.gov/>

Microgravity Research Division Home Page

NASA headquarters' Microgravity Research Division and microgravity sites with links to other news and programs and NASA Research Announcements
<http://microgravity.msad.hq.nasa.gov/>

Microgravity Research Program Home Page

Information about microgravity research activities with links to image archives and related science and technology web sites
<http://microgravity.msfc.nasa.gov>

Microgravity News

Online issues of *Microgravity News*, a quarterly newsletter about the field of microgravity science
<http://mgnews.larc.nasa.gov/>

Marshall Space Flight Center (MSFC) Home Page

Information about MSFC, current shuttle missions, the International Space Station, and research at MSFC's labs
<http://www.msfc.nasa.gov/>

Lewis Research Center (LeRC) Home Page

Information on LeRC, including the work of its Microgravity Science Division and descriptions of special facilities, such as the Wind Tunnel Complex, the Propulsion System Laboratory, and drop towers
<http://www.lerc.nasa.gov/>

Jet Propulsion Laboratory (JPL) Homepage

Links to the latest news, status reports, and images from JPL's missions, as well as information about the laboratory at JPL
<http://www.jpl.nasa.gov/>

Microgravity Combustion and Fluids Database

Information on microgravity combustion science and fluid physics experiments
<http://www.lerc.nasa.gov/WWW/MCFEP/>

Microgravity Research Experiments (MICREX) Database

Information on microgravity experiments with a link to the European Space Agency (ESA) Microgravity Database
<http://otis.msfc.nasa.gov/fame/Fame.html>

ESA Microgravity Database

Experiment descriptions, results, diagrams, and video sequences
<http://www.esrin.esa.it/htdocs/mgdb/mgdbhome.html>

Zero Gravity Research Facility

Description and images of one of the LeRC drop towers
<http://zeta.lerc.nasa.gov/facility/zero.htm>

Shuttle Flights

Information on all shuttle flights to date
<http://www.hq.nasa.gov/osfl/shuttle/>

Shuttle/Mir Home Page

Description of NASA's Shuttle/Mir program, including information about collaboration between Russia and the United States
<http://shuttle-mir.nasa.gov/>

International Space Station

General and detailed information about the development of the International Space Station, including recent news, details of assembly, and images
<http://station.nasa.gov/core.html>

What Is Microgravity?

The definition of microgravity and how it is achieved
http://www.lerc.nasa.gov/Other_Groups/PAO/microgex.htm

Microgravity and Spaceflight

How microgravity is achieved and the importance of microgravity research
<http://microgravity.msad.hq.nasa.gov/aIntro/spaceflight.html>

LeRC Microgravity Science Division Educational Information

LeRC microgravity educational activities and links to other NASA educational sites
<http://zeta.lerc.nasa.gov/new/school.htm>

NASA Spacelink: A Resource for Educators

NASA education information, materials, and services, including NASA Educator Resource Centers
<http://spacelink.nasa.gov/>

Spacelink: Microgravity Teacher's Guide

Microgravity Teacher's Guide with physical science activities for grades 6–12
<http://spacelink.nasa.gov/Instructional.Materials/NASA.Educational.Products/Microgravity/>

Microgravity Meetings and Symposia

Bulletin board of meetings, conferences, and symposia, and a list of societies and web sites of interest to the microgravity science community
<http://zeta.lerc.nasa.gov/ugml/ugml.htm>

Funding for the Microgravity Research Program (MRP) in fiscal year (FY) 1997 totaled \$134.3 million. This budget supported a variety of activities, including an extensive microgravity research and analysis program; development and flight of microgravity shuttle and sounding rocket missions; International Space Station (ISS) planning, technology, and hardware development; and educational outreach. The funding distribution for combined flight and ground efforts in the various microgravity research disciplines is illustrated in Figure 1.

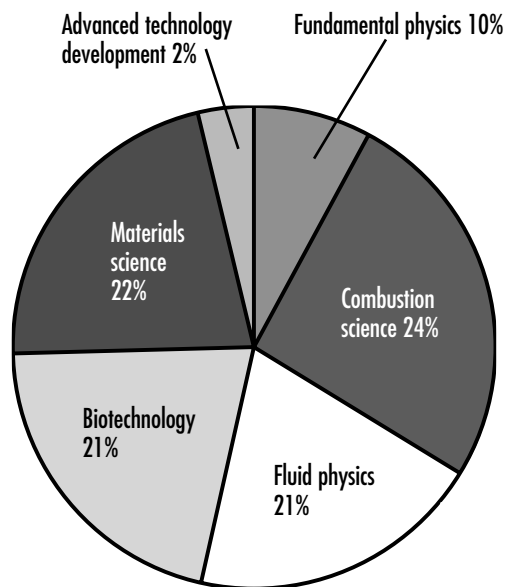


Figure 1 — FY 1997 microgravity funding distribution by science discipline: \$134.3 million

Figure 2 presents the funding distribution by microgravity mission. Included in this representation is the research and analysis element, which supports the ground-based microgravity principal investigators not covered in a mission-specific budget. The multimissions category includes costs not identified with a specific mission, such as administration, the Advanced Technology Development Program, science support activities, data management and archiving, National Institutes of Health cooperative activities, and infrastructure. The small missions element is the portion of the MRP using the space shuttle small payload systems, like the Get Away Special Program, shuttle middeck experiments, and sounding rockets. The space station element represents funding for the ISS and *Mir* programs.

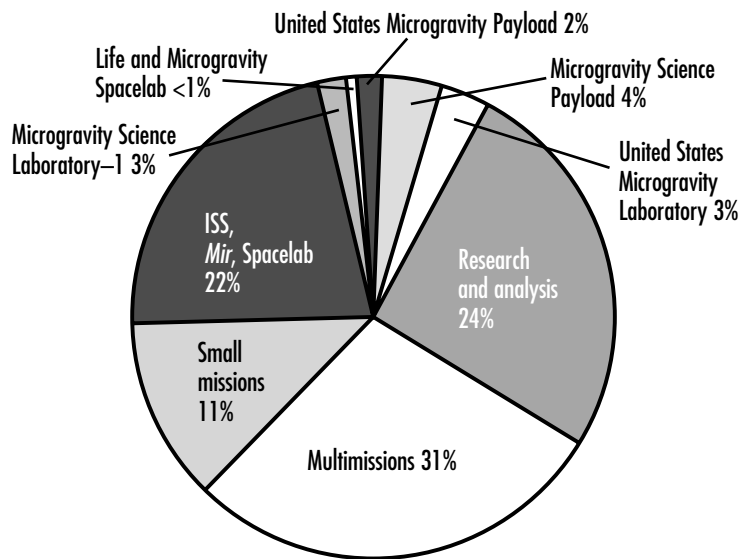


Figure 2 — FY 1997 microgravity funding distribution by series: \$134.3 million

The MRP operates through four NASA field centers. Figure 3 illustrates the funding distribution among these centers (and includes NASA headquarters funding for the Microgravity Research Division). The MRP science discipline authority and major responsibilities are as follows:

- Jet Propulsion Laboratory — fundamental physics.
- Johnson Space Center — cell and tissue culture portion of the biotechnology discipline.
- Lewis Research Center — combustion science, fluid physics, and microgravity measurement and analysis.
- Marshall Space Flight Center — biotechnology, materials science, and the glovebox program.

Technology development tasks were also funded at each of the NASA field centers in FY 1997.

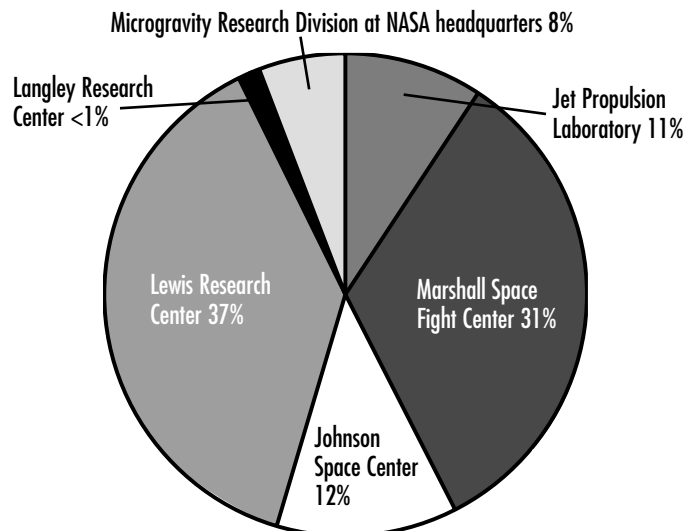


Figure 3 — FY 1997 microgravity funding distribution by NASA field centers: \$134.3 million

NASA's goal is to improve the quality of life on Earth by using ground- and space-based research to promote new scientific and technological discoveries. The Microgravity Research Program plays a vital role in our nation's economic and general health by carefully selecting, funding, and supporting scientists across the country. It also serves as an important link in the international endeavors that are the hallmark of America's space program, which is conducting business better, cheaper, and faster through cooperative ventures and other streamlined practices.

By disseminating knowledge and transferring technology among private industries, universities, and other government agencies, NASA's Microgravity Research Program continues to build on a foundation of professional success, evidenced by the number of publications and conferences attended, while reaching out to encompass the populace at large. Educational outreach and technology transfer are among the program's top goals, making the benefits of NASA's research available to the American public. Space shuttle and *Mir* research missions, as well as experiments performed in short-duration microgravity facilities, are yielding new understanding about our world and the universe around us, while paving the way for long-duration microgravity science on the International Space Station.

For more information about NASA's Microgravity Research Program, use the following contact information:

Microgravity Research Division
NASA Headquarters
300 E Street, S.W.
Washington, DC 20546-0001

Fax: (202) 358-3091
Phone: (202) 358-1490

World Wide Web addresses:
<http://microgravity.msad.hq.nasa.gov>
<http://microgravity.msfc.nasa.gov>

10 Abbreviations and Acronyms

AADSF	Advanced Automated Directional Solidification Furnace	FSDC	Fiber-Supported Droplet Combustion
AC	alternating current	FY	fiscal year
AIDS	acquired immunodeficiency syndrome	GAS	Get Away Special
AMMSA	Alliance for Microgravity Materials Science and Applications	GN ₂	gaseous nitrogen
ATD	Advanced Technology Development	GRP	gravitational and relativistic physics
BDPU	Bubble, Drop, and Particle Unit	GSFC	Goddard Space Flight Center
BDU	Bioreactor Demonstration Unit	GSM	Gas Supply Module
BEC	Bose-Einstein condensation	GSRP	Graduate Student Research Program
BIO-3D	Biochemistry of Three-Dimensional Tissue Engineering	HEDS	Human Exploration and Development of Space
BRS	Bioproduct Recovery System	HIV	human immunodeficiency virus
BSTC	Biotechnology Specimen Temperature Controller	HQ	headquarters
BTF	Biotechnology Facility	IDGE	Isothermal Dendritic Growth Experiment
BTR	Biotechnology Refrigerator	IML	International Microgravity Laboratory
BTS	Biotechnology System	IPCG	Interferometer for Protein Crystal Growth
CAPSI	Caltech Precollege Science Initiative	ISS	International Space Station
ChEx	Confined Helium Experiment	JPL	Jet Propulsion Laboratory
CM	Combustion Module	JSC	Johnson Space Center
CoDR	concept design review	KSC	Kennedy Space Center
CPL	capillary-pumped loop	LCAP	laser cooling and atomic physics
CSA	Canadian Space Agency	LeRC	Lewis Research Center
CSLM	Coarsening in Solid-Liquid Mixtures	LIF	Large Isothermal Furnace
CVX	Critical Viscosity Experiment	LII	laser-induced incandescence
DARTFire	Diffusive and Radiative Transport in Fires	LMD	Liquid Metal Diffusion
DC	direct current	LMS	Life and Microgravity Spacelab
DCAM	Diffusion-Controlled Protein Crystallization Apparatus for Microgravity	LPS	Liquid-Phase Sintering
DCE	Droplet Combustion Experiment	LSP	Laminar Soot Processes
DLR	German Aerospace Research Establishment	LTCMP	low-temperature and condensed matter physics
DPIMS	Diffusion Processes in Molten Semiconductors	LTMPF	Low-Temperature Microgravity Physics Facility
DYNAMX	Critical Dynamics in Microgravity	LTSE	Low-Temperature Science and Engineering
EDMP	Experiment Data Management Plan	MEPHISTO	Apparatus for Studying Interesting Solidification Phenomena on Earth and in Space
ESA	European Space Agency	MGBX	Microgravity Glovebox
EXPRESS	EXpedite PROcessing of Experiments to Space Station	MGBX	Middeck Glovebox
FCF	Fluids and Combustion Facility	MGMG	Microgravity Measurements Group

MICREX	.....	Microgravity Research Experiments	STDCE	.....	Surface Tension-Driven Convection Experiment
MIM	.....	Microgravity Isolation Mount	STEP	.....	Satellite Test of the Equivalence Principle
MISTE	.....	MIcrogravity Scaling Theory Experiment	STES	.....	Single-Locker Thermal Enclosure System
MMA	.....	Microgravity Measurement Assembly	STS	.....	Space Transportation System
MRD	.....	Microgravity Research Division	SUE	.....	Superfluid Universality Experiment
MRP	.....	Microgravity Research Program	TAS	.....	True Air Speed
MRPO	.....	Microgravity Research Program Office	T _c	.....	critical temperature
MSFC	.....	Marshall Space Flight Center	TEMPUS	.....	Electromagnetic Containerless Processing Facility
MSG	.....	Microgravity Science Glovebox	UCSB	.....	University of California, Santa Barbara
MSL	.....	Microgravity Science Laboratory	UF	.....	Utilization Flight
MSRF	.....	Materials Science Research Facility	USML	.....	United States Microgravity Laboratory
MSRR	.....	Materials Science Research Rack	USMP	.....	United States Microgravity Payload
MW	.....	molecular weight	VDA	.....	Vapor Diffusion Apparatus
NIH	.....	National Institutes of Health	WCI	.....	Wetting Characteristics of Immiscibles
NRA	.....	NASA Research Announcement	WWW	.....	World Wide Web
OARE	.....	Orbital Acceleration Research Experiment	Zeno	.....	Critical Fluid Light Scattering Experiment
PCAM	.....	Protein Crystallization Apparatus for Microgravity			
PD	.....	Program Development			
PI	.....	principal investigator			
PMMA	.....	polymethyl methacrylate			
QSAM	.....	Quasi-Steady Acceleration Measurement			
RDR	.....	requirements definition review			
RG	.....	renormalization group			
RSV	.....	Respiratory Syncytial Virus			
SAL	.....	Spread Across Liquids			
SAMS	.....	Space Acceleration Measurement System			
SAMS-FF	.....	Space Acceleration Measurement System for Free Flyers			
SCR	.....	science concept review			
SOFBALL	.....	Structure of Flame Balls at Low Lewis Number			
SPIE	.....	Society for Photo-Optical Instrumentation Engineers			
SQUID	.....	Superconducting Quantum Interference Device			
SSFF	.....	Space Station Furnace Facility			
STAC	.....	Scientific and Technological Advisory Council			